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SOUND

AND ITS RELATION TO MUSIC

BY

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DEDICATION

To my very dear friend
Professor Hamilton C. MacDougall

PREFACE

Every intelligent musician should be familiar with the physical laws which underlie his art. In the following pages will be found a compact statement of these laws and of the chief facts, theories and experiments in accordance with which they have been formulated. The nature and transmission of sound, its various elements and manifestations, the musical materials derived from it and the application of these materials in the construction of instruments are some of the matters discussed.

In order to facilitate further reading in regard to any of the subjects broached, references are given at the end of each chapter to correlative parts of important works on acoustics, of which a list is appended. Abstruse mathematical works like those of Airy or Lord Rayleigh are excluded. Books are referred to in individual chapters simply by the last names of their authors

Scientists and musicians have been slow in coöperating, and at times have even antagonized each other. It is hoped that in the future mutual helpfulness will take the place of distrust, and that due allowance may be made by either party for slight points of divergence between mathematics and æsthetics. That the present book may aid toward this result is the earnest wish of its author.

Clarence G. Hamilton.

Wellesley, Mass., June, 1911.

CONTENTS

Marcus M. Henry — Musical Manager — San Francisco — California

LIST OF REFERENCE BOOKS

BARNES, C. L. *Practical Acoustics.*
Macmillan and Company, London, 1909. $1.10.
Consists mainly of a series of experiments.

BARTON, EDWIN H. *A Text-book on Sound.*
Macmillan and Company, London, 1909. $3.00.
A highly technical treatise. Illustrated.

BLASERNA, PIETRO. *The Theory of Sound.*
D. Appleton and Company, New York, 1876. $1.50.
Readable and non-technical. Illustrated.

BROADHOUSE, JOHN. *Musical Acoustics.*
William Reeves, London. Fourth edition, 1905. $3.00.
"The Student's Helmholtz." Illustrated.

CATCHPOOL, EDMUND. *A Text-book of Sound.*
W. B. Clive, London, 1894. $1.50.
Somewhat technical in character. Illustrated.

HARRIS, T. F. *Handbook of Acoustics.*
J. Curwen and Sons, London. Revised 1910. $1.25.
A well-outlined treatment, with examination questions. Illustrated.

HELMHOLTZ, H. L. F. *The Sensations of Tone.*
Longmans, Green and Company, London. Third edition, 1895. $9.50.
The standard work on acoustics.

LAVIGNAC, ALBERT. *Music and Musicians.*
Henry Holt and Company, London. Revised 1907. $1.75.
The first part contains a concise treatment of acoustics.

POLE, WILLIAM. *The Philosophy of Music.*
Trübner and Company, London, 1879. $3.00.
Discusses the materials used in music.

POYNTING AND THOMPSON. *Sound.*
Charles Griffin and Company, London, 1909. $2.75.
Somewhat technical. Fully illustrated.

STONE, W. H. *Elementary Lessons on Sound.*
Macmillan and Company, London, 1895. $0.90.
A compact treatise. Illustrated.

TAYLOR, SEDLEY. *Sound and Music.*
Macmillan and Company, London, 1883. $2.50.
Written in an interesting style.

TYNDALL, JOHN. *Sound.*
D. Appleton and Company, New York. $2.00.
A standard popular work. Illustrated.

ZAHM, J. A. *Sound and Music.*
A. C. McClurg and Company, Chicago, 1892. $2.00.
Very readable and fully illustrated.

SOUND, AND ITS RELATION TO MUSIC

CHAPTER I

THE ORIGIN AND TRANSMISSION OF SOUND.

THROUGHOUT the recorded course of human history, investigations into the nature and properties of sound have occupied the attention of philosophers and scientists. As early as the sixth century B. C., Pythagoras demonstrated the laws of sounding strings; and it is probable that his researches were founded upon data derived from the Egyptians. Others of the Greek philosophers, as well as those of following centuries, propounded and speculated upon the various and complex acoustic problems, sometimes giving to them answers which have afterward been found logical and demonstrable. It was only during the intense scientific activity of the latter half of the nineteenth century, however, that a really competent exposition of the subject appeared. In 1862 the distinguished German scientist Helmholtz (1821-1894) published his epoch-making work on *The Sensations of Tone.* This was supplemented by the labors of other enthusiasts, such as Tyndall (1820-1893) in England and Koenig (1832-1901) at Paris. By interesting and convincing experiments these men succeeded in clearing up mysterious points which had baffled the wits of sages for centuries, and in bringing to light many facts destined to aid immeasurably the comprehension of that most elusive of all the arts, music.

Investigations of sound-phenomena.

The fundamental proposition upon which all these researches rest is that **the physical basis of sound consists in a form of motion.** This fact is so patent as scarcely to need further demonstration: we can easily observe the whirring of the violin string as it is agitated by the bow, and

Sound a form of motion.

can feel the trembling of the bell after it has been struck by the clapper; nevertheless, a few simple experiments may still further attest its truth.

Let a pith ball be suspended so that it hangs close to one of the prongs of a tuning-fork. (Fig. 1.) If now a violin bow be drawn across the fork so as to produce a tone, the ball will be thrown violently to one side, and will be repeatedly repelled whenever it rebounds against the fork, thus showing that the fork is in a state of agitation while sounding. Or, let a chalked string be suspended over two bridges *A* and *B* (Fig. 2) in front of a blackboard, with one end of the string wound about a pin at *C*, which can thus regulate its tension. If the string be now plucked in the middle, its vibrations will be seen plainly, and when the tension is increased by turning the pin *C*, these vibrations will become still more rapid.

Proofs of this from sounding tuning-fork and string.

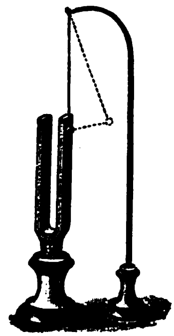


Fig. 1.

Besides taking its rise in the motions of solid bodies, sound may also be produced by the shock occasioned when a liberated gas comes violently into contact with the air in an explosion, or even by the agitation of a sequestrated portion of the air itself, such as occurs in an organ pipe. An illustration of this latter phenomenon will be found on page 75.

Sound from gases or from confined air.

Let us now return to our tuning-fork. Affixing a little metal point to each prong and drawing these points rapidly over a piece of smoked glass while the fork is sounding, we produce a wavy line, as in Fig. 3. Examining this line, we find that it is composed of regular curves which run alternately to one side and to the other. Our deduction from this discovery is that each prong swings continually to and fro, in the

Examination of the vibrations of a tuning-fork.

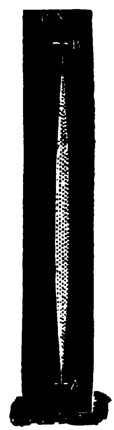


Fig. 2.

manner of a pendulum. Starting from a point of rest, it is

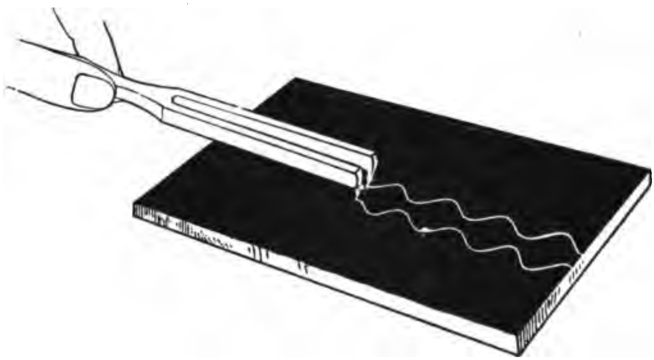


Fig. 3.

impelled by the violin bow a given distance in one direction, where it becomes motionless for an instant. It then rebounds to its first position, and immediately performs a similar evolution in the opposite direction. When it has again returned to its starting point it has made what is called a *complete vibration.* If it should then stop, the air would carry a single explosive blow to our ears; but, impelled by the impetus which it has received, the prong continues to vibrate with lessening force, until it returns to rest, or until the bow again agitates it. A number of vibrations of similar character thus occurring in regular sequence are said to be *periodic*, and the sound which they produce is of uniform pitch.

Periodic vibration.

Let us note that, in order to be capable of performing such vibrations, a body must possess what is called *elasticity,* which means the power of rebounding to its original position after some force has driven it to one side. An instance of this action is seen in an ordinary elastic band. We make use of this to hold objects together by the force which it constantly exerts after it has been stretched, and which, if allowed to do so, would snap it back vigorously into its normal condition.

Nature of the property of elasticity.

The vibrations of the tuning-fork which we examined were all *simple:* that is, they produced perfectly uniform curves on either side of the wavy line. As a matter of fact, however, such simplicity is seldom found in the motions of a sounding body; for, as a general rule, these are accompanied by other vibrations of different extent and rapidity, while sometimes a mingling of all sorts of motions takes place. The sound made by the impact of the fingers upon the piano keys, for instance, is mingled with the musical tones, as is the scraping of the violin bow across the strings, and the hissing of the air at the mouth of the organ pipe. When the vibrations are periodic, and are either simple or else accompanied by subordinate vibrations which are indistinguishable or have simple relations to the primal sound, the complete sound is said to be *musical* in character, and its fundamental effect is spoken of as a *tone.* According as the more complex or irregular vibrations become prominent in the sound, does it lose in its musical value; and when all semblance of regularity has disappeared, tone vanishes, and the sound is described as mere noise. It is evident, therefore, that no sharp line of demarkation exists between musical and non-musical sounds, and that a classification of the doubtful cases must depend largely upon personal opinion.

Tone and noise.

When we inquire, on the other hand, what kinds of sounds are available for the use of the musician, other considerations arise. However musical the tone, it must be put into a practicable form. The sound given out by the falls of Niagara, for instance, has been analyzed and found to have decided musical characteristics, since it possesses a strongly-marked fundamental tone and harmonious accompanying tones; but this rich combination could hardly be introduced into a musical composition, except by proxy. The substitutes for any desired sounds of nature must be found in either the human voice or artificial musical instruments. These latter have been devised and elaborated to such an extent that the modern composer has at his command most of the

Sounds available in music.

typical varieties of tone, each through an adequate compass of pitches.

In his compositions, therefore, the musician makes use in the first place of instruments like the violin, which can produce tone pure in its make-up and steady in its pitch. Next, however, he employs special means for emphasizing the element of *rhythm;* for it must be remembered that *regular pulsation* is as important a factor in musical structure as melodic beauty. Thus instruments of percussion are also necessary, in which an explosive sound marks off the divisions of time. Some of these instruments, like the kettle drum, have a distinct fundamental tone; while others, like the snare drum, give out merely a confused noise. Then, too, while the composer bases his work upon conventional instruments, he feels at liberty to introduce those of a bizarre character, like the tam-tam, or queer effects, like the rapping of the violin bow on the wood of the violin, in order to express some extraordinary conception. The sounds which he is least likely to employ are those which are unreliable in pitch, like those of the siren (page 26), since such sounds are subversive of those definite intervals which form the substructure of music, and give to it stability.

Types of musical instruments.

For the present, we shall consider only those sounds which are produced by simple vibrations. We pass, therefore, to the discussion of the manner by which these vibrations are able to reach our ears, when originating in objects entirely external to ourselves. Generally, the sound reaches us through the intervening air, and it can easily be shown that, while other media may serve as sound-transmitters, **a medium of some description must be employed for the purpose, and that without this, no sound can be heard.** In

Necessity for a medium as a sound-transmitter. Proof of this.

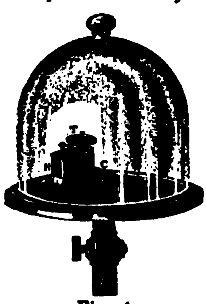


Fig. 4.

Fig. 4 a bell *T*, placed upon a plate that is connected with an air-pump, is kept sounding by means of a clock-work attachment *H C;* and over the whole a bell-glass is placed. The sound at first continues with almost undiminished intensity, but as the air is exhausted by the pump, the sound grows fainter, and when a practical vacuum is produced, it is inaudible. Care has been taken to place the clock-work upon a piece of non-conducting material, otherwise the vibrations would have been carried to the outer air by the plate itself. If, now, hydrogen, which is fifteen times lighter than air, be admitted within the glass, a faint sound is heard. Hence we conclude that **the sound decreases as the medium through which it passes becomes attenuated.** This latter fact has been further attested by experiments with other gases and vapors. Solids, also, are often good transmitters of sound. Deaf persons, for instance, are enabled to hear distinctly, when the auditory nerve is unimpaired, by holding an apparatus between their teeth which catches the sound-vibrations from the external air, whence they are conveyed to the ear through the intervening bones of the head.

Action of a vibrating rod upon the air.

To understand how vibrations are imparted to the air by a sounding body, we must first remember that the air is composed of an inconceivably great number of particles or molecules, roughly estimated as a million billions to a cubic centimeter, or cube one side of which is about three-eighths of an inch long. Placing a metallic bar *A B* in a vise *E C* (Fig. 5), we set the free part *A C* into a pendulum-like motion by drawing it to one side at the point *A*. If the free part has been made long enough, we can easily see this oscillate from *a* to *a'*, and no sound will be heard. The reason for this latter fact is that the vibrations are made so slowly that the air-particles have

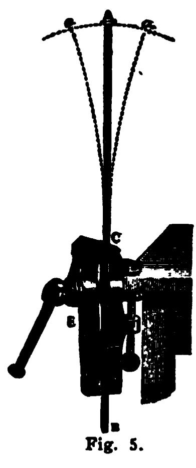


Fig. 5.

time to slip out of the way before the onset of the bar. If now the free part be made gradually shorter, the vibrations will grow faster, and will finally be so blended together that they are indistinguishable. At a certain point, too, a low tone will be heard. This tone arises from the fact that the air-particles no longer have time to avoid the bar as it approaches, and are therefore hit by it at each of its attacks. When the particles next to the bar are thus affected, they are thrown violently against those next to them, which in their turn transmit the impulse to their neighbors. This crowding together of particles, or *condensation,* as it is called, now passes along rapidly from one series of particles to another in all directions away from the bar.

The wave of condensation.

But after the rod has forced together the particles which obstruct its passage, it immediately springs back in the opposite direction, leaving in its track a space which is rendered practically empty of particles, and which is thus said to be *rarefied.* This wave of rarefaction follows immediately after that of condensation, just described. Again the rod attacks, and another wave of condensation starts out, succeeded as before by a wave of rarefaction; and these alternate conditions are repeated, so long as the rod continues to vibrate.

The wave of rarefaction.

The manner in which the waves proceed from the sounding object to the ear of the listener is graphically portrayed in Fig. 6. One of the prongs of the tuning-fork here represented produces vibrations in exactly the same way as the metal bar which we have taken as our model. In actual computations, a complete

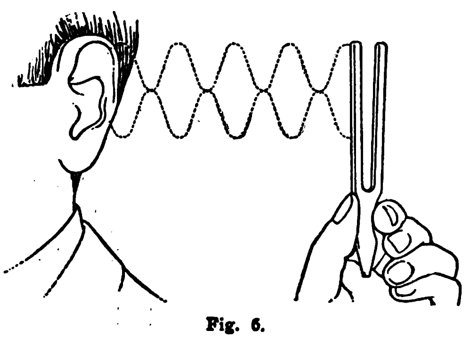


Fig. 6.

sound-wave is made to consist of the sum of a condensation and a rarefaction. Hence **the length of a sound-wave will be equal to the distance from any given point in a condensation to a similar point in the next condensation, or from a given point in a rarefaction to a similar point in the next rarefaction.**

Action and length of a sound-wave.

It is important to notice that the air-particles, when thus acted upon, do not move permanently from their original positions. If they were blown along by each sound-wave, we should feel a draught of air with each sound which reaches us. But the particles act much as do the blades of wheat when a breeze sweeps over the wheat-field, driving these aside only temporarily. In the case of the air-particles, however, each performs a complete vibration for each sound-wave, corresponding to that of the sounding body. How this motion is accomplished can be seen by the use of the stand shown in Fig. 7, invented by Mariotte over two hundred years ago. In this, an impulse given to one of the balls *A* travels through the entire line of balls, while each one is stopped in its course by the push which it transmits to the next. Only the end ball C flies off to a greater distance, the others becoming motionless. Thus does the sound reach the ear, while the intervening air-particles return to their original places unless again set in vibration by the sounding body. Sound-waves are also frequently compared with the waves which arise when a stone is dropped into the water. As with air-particles, the water-particles perform an oscillating evolution, returning finally to their normal places. But

The vibration of air-particles.

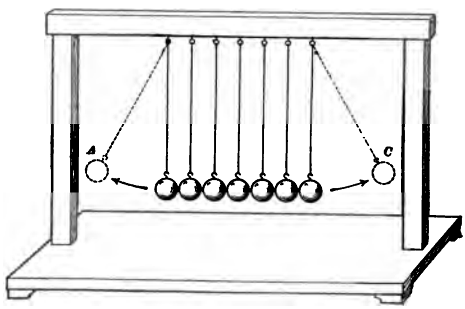


Fig. 7.

Sound-waves compared with water-waves.

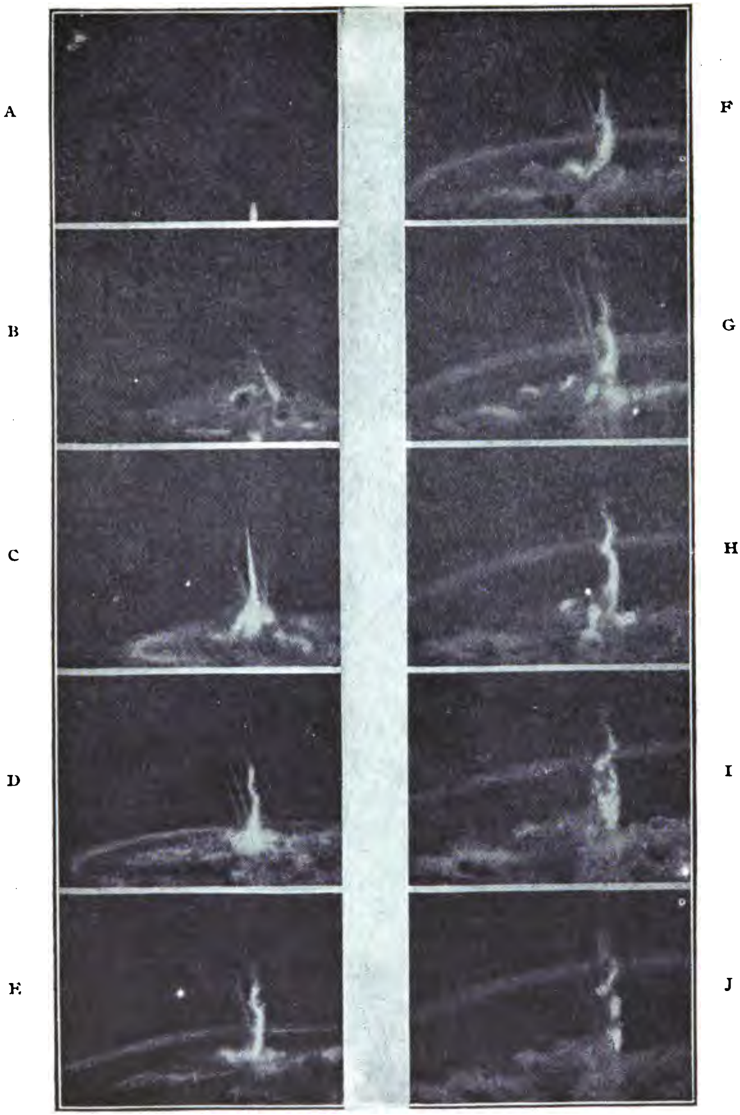


Fig. 8.

while the water-particles have an up and down motion, the air-particles move forward and back; and also, while the water-waves move simply along the surface of the water, the sound-waves swell out into the form of a sphere, of which the radius is constantly and rapidly increasing.

Visible Sound-waves.

Under ordinary circumstances sound-waves are imperceptible to any of the senses except that of hearing. Heavy detonations, however, such as the roll of thunder or the report of a cannon, can be felt as well as seen; and in certain cases sound-waves have become visible. Professor C. V. Boys, in 1897, succeeded in obtaining a series of kinematograph pictures of the explosion of a hundred and twenty pounds of a nitro-compound, taken at the unusually rapid rate of eighty exposures per second. In *A,* of the first ten of these, shown in Fig. 8, *A* to *J,* the smoke of the explosion appears rising gradually on the right. In the series *B* to *J* the sound-wave, in the form of a light ring, is seen rapidly expanding beyond the smoke of the explosion. Professor Boys says, "We stationed ourselves as near as prudence would allow, at a distance of one hundred and twenty yards, so that only about one-third of a second elapsed between the detonation and the passage of the shadow. The actual appearance of the ring was that of a strong, black, circular line, opening out with terrific speed from the point of explosion as a center."* In the pictures the black line does not appear, but only the light ring which must have accompanied it.

*See articles by Professor Boys in *Nature* for June 24, 1897, and by Prof. R. W. Wood, in *Popular Science Monthly* for August, 1900.

SUMMARY

SOUND is always produced by the vibratory motion of particles of matter, either in a mass or as individuals.

Musical sound, or tone, is produced by regular and periodic vibrations, and non-musical sound by irregular vibrations; but the lines of demarkation between the two are not sharply drawn, and the musician may employ for special effects many kinds of sound usually classified as noise.

Some medium is necessary for the transmission of the sound from its origin to the ear of the auditor. This medium is generally the air, in which the sound travels in waves, each consisting of the sum of a condensation and a rarefaction.

In this transmission, the air-particles also move in vibrations. The sound-waves form a constantly enlarging sphere; and their motion is generally perceptible only to the sense of hearing.

REFERENCE LIST.

Helmholtz, Chapters 1 and 2.
Zahm, Chapter 1.
Tyndall, Chapters 1 and 2.
Taylor, Chapter 1.
Broadhouse, Chapters 1-4.
Harris, Chapters 1 and 2.
Catchpool, Chapters 1 and 2.
Stone, Introduction, and Chapters 1 and 2.
Poynting and Thompson, Chapter 1.
Blaserna, Chapters 1 and 2.
Barnes, Chapters 1 and 2.
Barton, Chapter 1.
Lavignac, Chapter 1, A.

CHAPTER II

Velocity, Reflection, Refraction and Diffraction.

The rapidity with which sound is transmitted through any medium is dependent upon two factors, the one of which is the *density* of the medium, and the other its *elasticity*. Of these, the former tends to retard, and the other to accelerate the sound.

Factors affecting velocity of sound.

We have stated that all matter is made up of a vast quantity of inconceivably small particles. The number of those present in a given bulk of matter is said to constitute its *density;* and this density becomes greater or less according as the number of particles increases or diminishes. A change of condition or location, however, may affect this number to a considerable degree. We know, for instance, that the air on a mountain top is much less dense (or more rarefied) than that in the valley beneath.

Condition of density.

Through this mass of particles the sound-waves proceed at a rate which, though extremely rapid, is yet easily appreciable by the senses. We have all, when seated in the rear of a large concert hall, noted how the beats of the orchestral conductor seemed curiously to precede the sounds which they evoked. This illusion arises from the same principle which causes the lightning flash to be visible sometimes many seconds before its accompanying crash of thunder is audible: namely, that light travels much faster than sound.

Light faster than sound.

The velocity of light, computed at about 190,000 miles per second, is so great, that, for terrestrial distances, the time which it occupies in travelling from its source to the eye of the beholder is practically negligible. This fact may therefore be used to advantage in determining sound-velocity. Let a cannon be fired at a known distance, and the time which elapses between the flash and the report be recorded. Evidently, if the entire distance be divided

Determination of sound-velocity by flash of light.

by the ascertained number of seconds, the result will be the distance traversed in a single second, which distance is generally used as the unit of measurement.

For purposes of extreme accuracy, however, this experiment must be conducted with much more care. Several disturbing factors, the chief ones of which are the wind, the temperature, and the moisture, are almost invariably to be reckoned on. The most important of these is the wind, which carries the sound faster when it is moving in the same direction, and retards it when the directions are in opposition. In the first accurate experiments upon the velocity of sound, made by the French Academy of Sciences in 1738, cannon were fired at three stations visible from the Paris Observatory, but at some distance away, a report taking place at one of the stations every ten minutes. The time-intervals between the flashes and reports were recorded and afterwards averaged. In a similar experiment, in 1822, it was sought still further to eliminate the influence of the wind by firing cannon alternately at each of two stations about twelve miles apart. The time for the light and sound of each report to reach the opposite station was noted, and the mean between the figure arrived at by each set of observers was finally adopted. In subsequent experiments even more pains were taken to secure exactness, such as the employment of electrical devices to record the arrival of the flashes and reports, in order to eliminate the slight error arising from the portion of time necessary for the observer to realize and then record the sensation received.

Experiments on this basis.

The velocity of sound thus determined was found to be 1090 feet per second when the temperature of the air was at the freezing point. This velocity increased, however, with a rising temperature, at the rate of about a foot for each degree Fahrenheit. Consequently, **at the ordinary temperature, 1120 feet per second may be regarded as sufficiently accurate for rough calculations;** a speed nearly thirteen times as fast as the fastest express train.

Resultant figures.

If the number of seconds between the perception of a light and its sound be multiplied by this velocity per second, the result will evidently be the distance of the sounding object. We may thus estimate the distance of a lightning discharge by counting the number of seconds between the flash and its accompanying peal of thunder, and allowing something less than five seconds to a mile.

Determination of the distance of a sounding body.

Before the above experiments had taken place, Sir Isaac Newton (1642-1727) had calculated sound-velocity by laboratory methods and had secured figures about a sixth smaller than those we have given. It was afterward discovered, however, that the sound-waves themselves produced a slight rise in temperature which effected this difference. Other experiments at short distances and of a more complicated character have served to verify the accepted figures.

Verification by different experiments.

Father Mersenne (1588-1648) calculated sound-velocity by noting the time which it took for an echo (page 19) to reach him, and the distance of the reflecting object. As the sound must travel to this object and back again, it follows that a division of twice the distance of the object by the number of seconds required for the echo to return will give the velocity per second. It is hardly possible, however, to secure extreme accuracy by this method.

Velocity calculated from echoes.

While a variation in temperature produces a corresponding variation in sound-velocity, it is nevertheless true that **the velocity remains the same, however much the density of the air may fluctuate.** The cause of this phenomenon is that with an increase in the density, there is an exactly proportional increase in the elasticity of the air; hence the ratio between the two factors remains constant.

Effect of varying densities of air.

As a general rule, too, **whatever the pitch or other characteristics of the sound, its velocity is the same. If this**

were not true, we should hear sounds at a distance in varying order from that of their production, and the music from a brass band, for instance, would reach us in inextricable confusion. It has been pretty well proved, however, that extraordinarily loud sounds may have an increase of velocity over those of ordinary intensity. An interesting example of this exception was afforded on one of Parry's arctic voyages, in 1822, when, at a distance of two and a half miles, the order to fire a cannon was heard *after* the report.

Velocity in air not affected by character of sound.

In other media the velocity of sound is frequently much different from what it is in air. Experiments made by means of long tubes and organ pipes have produced the following rates per second in gases, at the freezing point of air, or 0° Centigrade:—

Velocity in gases.

Oxygen	1040 feet
Hydrogen	4164 feet
Carbon dioxide	858 feet
Carbon monoxide	1107 feet
Nitrous oxide	859 feet
Olefiant gas	1030 feet

Important experiments as to velocity in water were made by two French physicists in 1827, on the Lake of Geneva. Stationed in boats on opposite sides of the lake, one of them took charge of the sound-production, while the other recorded the results with a stop-watch, listening through an ear trumpet *O M* (Fig. 9), held in the water. The source of sound was the bell *C*, struck by the hammer *B*. The lever which impelled *B* simultaneously ignited a flash of gunpowder by the

Velocity in liquids.

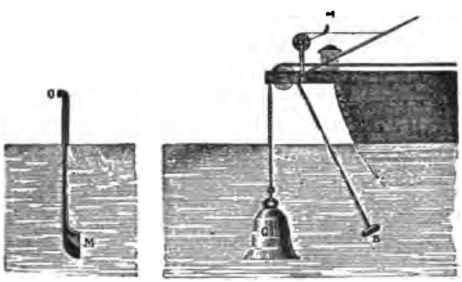


Fig. 9.

torch *M*. It was thus found that the velocity of sound in water at 8.1° C. was 4,707 feet per second, or more than four times what it is in air. Different figures have resulted from experiments with other liquids, though the increase of velocity over that in air is considerable in each case. The reason for this fact is that, although liquids are more dense than air, their elasticity is still greater in proportion.

In most of the solids, the same conditions exist. In metals, the velocity varies from four to sixteen times its rate in air.

Velocity in solids.

In wood, the velocity is greater in the direction of the fibre than across the rings. In the former direction, it varies in different woods from ten to sixteen times its rate in air. The greatest velocity is found in iron and steel, of the metals, and fir and aspen, of the woods. It should be noted that an augmentation of temperature, which increases the velocity in gases and liquids, has generally the opposite effect upon the velocity in metals.

Wood is an especially good conductor of sound. To illustrate this characteristic, wrap up a music box in several

Experiments with wood.

thicknesses of felt, a non-conductor of sound, so that the sound is made as nearly inaudible as possible. If, now, the end of a rod of wood three or four feet long be inserted in the wrappings and rested on the lid of the box while it is playing, the sound-vibrations will be plainly felt along the rod by the hand, and, on applying the ear to the other end of it, the music will be heard with greatly increased intensity. Place a guitar or violin against the free end of the rod, and the vibrations will be transmitted to it, so that the music seems to proceed from this instrument.

Another instance of the passage of sound through solids is afforded by the familiar *string telephone*, which consists of

Experiment with the string telephone.

two cardboard tubes, each having one end covered by a piece of parchment, through which passes a connecting string. Words whispered in one tube will be carried to a considerable distance through the string, and will reach the ear of the listener, placed at

the outer end of the other tube, with almost undiminished intensity.

In free air, sound-vibrations sometimes travel to very great distances. Instances are narrated of occasions when tremendous explosions have been heard for from five hundred to seven hundred and fifty miles. It is probable that the earth itself assists in carrying these vibrations; but Chladni (1756-1827) tells of hearing the sound from meteors the bursting of which indicated that they were a hundred and twenty-five miles in altitude. The amount of air affected by even slight sounds is sometimes enormous. Darwin speaks of crickets whose stridulations can be heard at night for the distance of a mile. In such a case, it is calculated that from five to ten million tons of matter are affected by the noise produced by an insect which weighs about a quarter of a pennyweight!

Travelling power of sound.

But sound rarely travels far without encountering some obstacle; and we now proceed to investigate what then happens. Sound is found to be subject to the same laws as are light and radiant heat, in that it suffers partial or total reflection. Let a sound produced at *A* (Fig. 10) strike the reflecting surface *D E* at the point *B*, making with it the angle *A B E*. The sound-wave will rebound in the direction of *C*, and the angle *C B D* will be equal to the angle *A B E*, following the law that **the angle of incidence is always equal to the angle of reflection.**

Law of reflection.

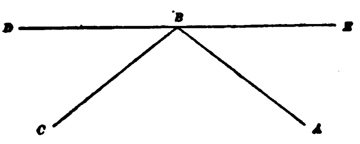


Fig. 10.

To demonstrate this law, take two long glass or cardboard tubes *A B*, and arrange them as in Fig. 11, with a flat card placed as a reflecting surface at *C*. Put a watch in the end of tube *A*, covering the opening with cloth so that the ticks are muffled. By listening at *B*, it will be discovered that the ticks are loudest when the

Demonstration of this law.

law of incidence and reflecion is complied with. Substitute other surfaces for the card, and compare their reflective power. Note that even a flat, or fish-tail, gas-flame will produce good results.

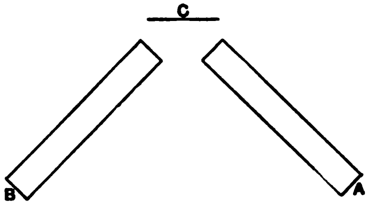


Fig. 11.

Progress of a soun^d-wave in reflection.

The sound-wave, meeting a flat surface, immediately changes its course, and travels as though it came from the opposite direction. In Fig. 12, the wave, striking the surface $A\ B$ at right angles, returns as if it had originated at O'; and the single ray $O\ I$ proceeds towards M, where it is heard as though coming from O'.

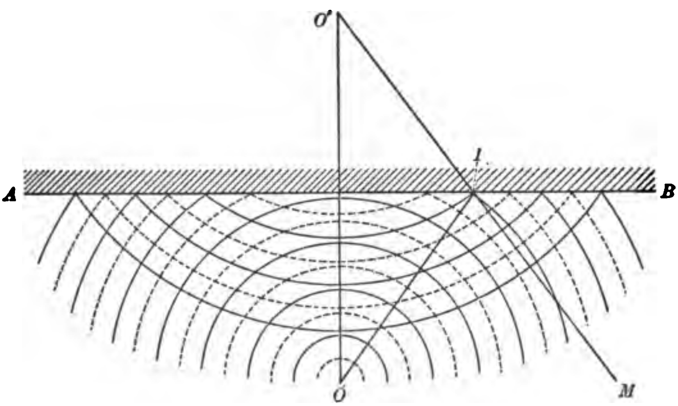


Fig. 12.

Experiments with curved mirrors.

Curved mirrors, like those at M and M' (Fig. 13), have the property of reflecting parallel rays of either light or sound to a single point called the *focus*, or, conversely, of reflecting

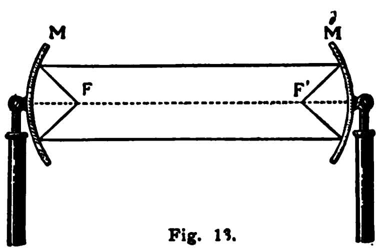


Fig. 13.

the rays from this focus in parallel lines. If a watch be suspended at the focus F of the mirror M (Fig. 13), and the parallel rays of sound reflected from M be concentrated on the mirror M', the ticking of the watch will be heard distinctly at the focus F', sometimes as far as two or three hundred feet from the watch.

Sound-reflection explains the familiar phenomenon of the *echo*. Objects having flat, plane surfaces are best adapted for this reflection; and according to the distance from the speaker will they give back one or more syllables. An object distant about 110 feet, for instance, will return one syllable only, while an object distant 220 feet will return two syllables, one 330 feet away three syllables, and so on. If these echoes themselves hit other reflecting surfaces, a second echo is produced, and sometimes this process is repeated as long as the vitality of the sound lasts. The result is a series of reverberations, such as those in the crypt of the Panthéon at Paris. Cases are cited where an echo has repeated the same sound as many as forty times. Mountainous regions, notably the cañons of the Rock Mountains, are especially susceptible to echoes. In large domes, like those of St. Paul's in London or the Capitol at Washington, the phenomenon of "whispering galleries" is frequently displayed. Conversations may be carried on in these by two persons close to the wall on opposite sides of the dome, which are inaudible to others only a short distance away. This effect is generally ascribed to a multiplicity of cross-reflections; although some physicists assert that the sound-waves under these conditions are not reflected, but run along the wall, just as water-waves follow the outline of a bank when they strike it at a small angle.

Phenomenon of the echo.

When sound-waves are reflected by surfaces only a few feet away from their origin, the tendency is to produce confusion. If the pulses of density exactly or nearly coincide in sounds thus moving in opposite directions, the result is an increase in intensity; but if the condensations of the original sound coincide with the rarefactions of its

Reflection at short distances.

echo, the result is a neutralization of both, and a consequent obliteration of the sound (page 41).

Considering, therefore, the manifold possibilities for conflict of reflections, it is not surprising that the acoustics of concert-halls present problems which have thus far proved insoluble. For musical purposes, a certain amount of sound-reflection is necessary in order to give life to the tones; but unless this reflection be admirably

Acoustics of concert-halls.

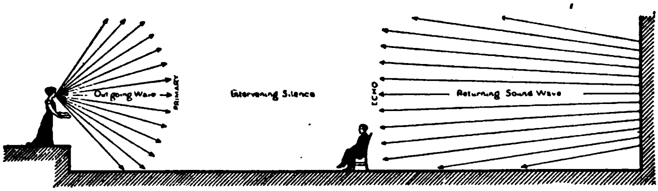


Fig. 14.

adjusted, confusion will occur in certain parts of the auditorium, or a *silence zone* may exist, such as that depicted in Fig. 14. In halls which have confusing echoes, resort is frequently had to deadening draperies, or to wires so stretched as to disperse the conflicting sound-waves.

Let us note that the resonance of the reflecting object sometimes affects quite decidedly the quality and power of the echoed sound, and occasionally also its pitch. Discussion of this phenomenon is reserved for Chapter VI.

Resonance as a factor in echo.

That a flat gas-flame (page 79) may also reflect sound is only an instance of an effect which may be produced by any gas or even any air-current of a temperature different from that of the surrounding atmosphere. The reverberation of thunder is thus caused not only by echoing clouds and solid objects, but also by varying currents of heated air. Tyndall proved by an elaborate series of experiments that air-currents were responsible for the great variation in the

Reflecting power of gases and air-currents. Fog signals.

distances at which fog-signals could be heard on different occasions. Sometimes, owing to these invisible reflectors, the signals could be heard only a short distance on a perfectly clear day; while at other times, when the air was filled with moisture, the distance which the sound travelled was surprisingly great. The loudness of sounds at night, too, is largely caused by the absence of the air-currents which are more likely to occur during the day time.

Speaking and ear trumpets.

Speaking trumpets and ear trumpets involve practical applications of the laws of reflection. In the former (Fig. 15), the sound in emerging is converted into parallel rays. Just what part the bell-shaped end plays in producing this result is not well known. In the ear trumpet the reverse process takes place, since the waves from the outer air become reinforced in the tube of the instrument, and thus reach the ear in greater volume.

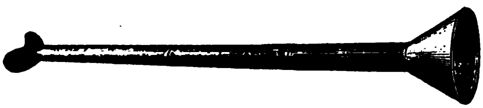


Fig. 15.

Demonstration of refraction.

Sound, like light, deviates from its course when it enters a medium of different density. This phenomenon is called *refraction*. In an apparatus designed by Sondhaus (1815-1886), shown in Fig. 16, carbonic-acid gas forced into a rubber bag *A*, which is supported in a broad brass ring *O O'* gives the bag the form of a double convex lens. We can demonstrate the fact that a sound produced at *S* comes to a focus just below *B* by strewing sand on a membrane at the

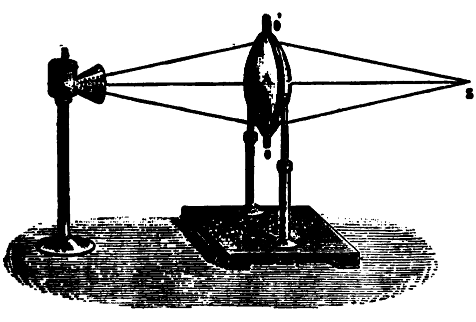


Fig. 16.

top of the box *B*, since the sand will dance about under the influence of the sound when the lens is present, but will remain quiet when the lens is removed. The focusing takes place because the sound-waves, on entering the denser gas, become flattened, and when they emerge the portion of the waves at the edges thus come to precede the interior portion, as in Fig. 17, finally concentrating at *B*.

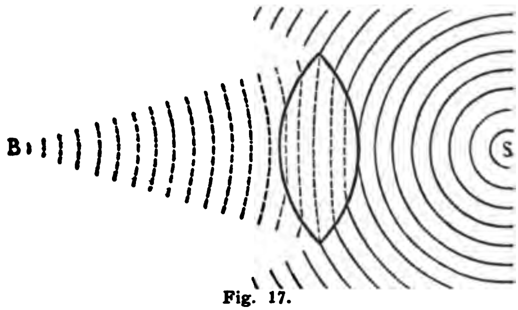


Fig. 17.

Sound-shadows and diffraction.

When a large object intervenes between a sound and the auditor, the sound loses in its intensity, and it may be quenched entirely, if the object be of sufficient size. The name of *sound-shadow* has been applied to this decrease. But if the opposing object be small, the sound-waves are bent around it, just as the water-waves dash around a small rock. This phenomenon is called *diffraction*. In cases of tremendous explosions of dynamite, it has been found that windows on all sides of houses in the path of the sound-waves were forced in: a result which is explained by this property of sound. If we listen to a railroad train as it dashes through tunnels and behind hills, the different grades of the sound-shadows will be apparent.

SUMMARY

Sound travels in air at the rate of 1090 feet per second when the temperature is at the freezing point, and one foot faster per second for each degree of rise, Fahrenheit. The velocity is the same, whatever be the density of the air.

Sound-velocity varies much in its rate in other media. In metals and woods it is several times as great as indicated in the above figures.

Together with light, sound possesses the power of reflection, refraction and diffraction.

In reflection, the angle of incidence is always equal to that of reflection. Reflection gives rise to echoes and reverberations. Smooth surfaces and even gases and air-currents are good reflectors.

By refraction, sound-waves can be driven from their course, and brought to a focus.

In diffraction, sound-waves are bent around objects of small size. When the opposing object is sufficiently large, a sound-shadow occurs.

REFERENCE LIST.

Tyndall, Chapters 1, 5, 7.
Zahm, Chapter 3.
Catchpool, Chapters 3, 8.
Harris, Chapter 2.
Blaserna, Chapter 2.
Stone, Chapter 2.
Lavignac, Chapter 1, B.
Poynting and Thompson, Chapter 2.
Barnes, Chapters 10, 11.
Barton, Chapter 10.
Broadhouse, Chapter 2.
Taylor, Chapters 1 and 7.

CHAPTER III

Pitch

As we walk along a country road and direct our attention toward the various sounds which reach our ears, we can, as a general rule, draw fairly accurate inferences as to their origins. We conclude that a shrill, piping note is produced by a bird perched on a near-by tree, and that the low, droning sound comes from a distant waterfall. Another low, but more rasping sound betokens the presence of a saw-mill; and from its direction and degree of intensity we assign it a position close to the waterfall.

Inferences from different sounds.

Since we are immediately conscious of the acuteness of the bird-notes as compared with the gravity of the tone of the waterfall, we distinguish between the two sounds primarily by their difference in *pitch*. But before we can separate the tone of the waterfall from that of the saw-mill, we must note their difference in *quality,* since their pitches are nearly alike. Finally, we conclude that the bird is close at hand, but that the other two objects are a mile or more away, from the proportional *loudness* with which the individual sounds reach us. These illustrations are cited as examples of the three properties of *pitch, loudness* and *quality* which all sounds possess, and which we now proceed to investigate.

Three properties of sounds.

Referring to Fig. 5 (page 6) we recall that the vibrations of the metal bar were distinguishable, before they produced a tone. When the bar was sufficiently shortened for the oscillations to give out a sound, however, the former were so fast that they lost their individuality; and, as the bar was further shortened and the sound consequently rose in pitch, the vibrations blended together completely. Similarly, if a violin string be plucked in the

Pitch dependent on vibration number.

middle, the whir of its vibrations is visible; but when the string is shortened and the pitch accordingly rises, these vibrations are seen to be much accelerated. From numerous experiments of this character, it has been proved that **the pitch of a sound depends on the number of vibrations of the sounding body: if these increase the pitch rises, and if they decrease the pitch falls.**

Devices for determining the number of vibrations. Savart's Wheel.

To determine the exact number of vibrations which a sounding body makes per second, a number of devices have been employed. The distinguished astronomer Galileo (1564-1642) found that in passing a knife-bladé over the milled edge of a coin a sound was produced which rose in pitch as the knife moved faster. A machine for measuring sound based upon this principle was invented by Savart (1791-1841). As shown in Fig. 18, this consists of a cog-wheel *B*, which can be rotated rapidly by means of the wheel *A*, connected with *B* by the belt *D*. If a card be placed against the cogs at *E* and the wheel turned slowly, a tap is heard each time that a cog releases the card. With an increase in quickness a sound is heard; and by noting the number of revolutions of *B* per second and multiplying this by the number of cogs on the wheel, the vibration number of this sound is obtained. If it be desired to ascertain the pitch of another sounding object, such as the tuning-fork *C*, the velocity of the wheel is regulated so that the pitches of the two sounds coincide, when the process just described will give the desired result.

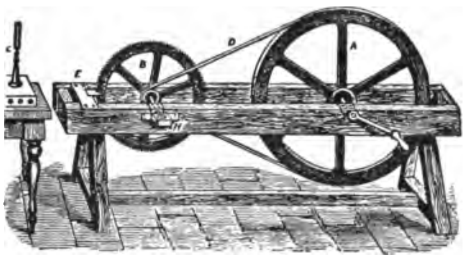


Fig. 18. Savart's Wheel.

Another instrument, which produces sound-vibrations by means of puffs of air, is the invention of Cagniard-Latour

Latour's siren. (1777-1859), and is called the *siren* (Fig. 19). In this, a disk *s s*, having a circular row of holes, revolves over a plate similarly perforated. This latter plate forms the top of a hollow chest *A A*, from which wind,

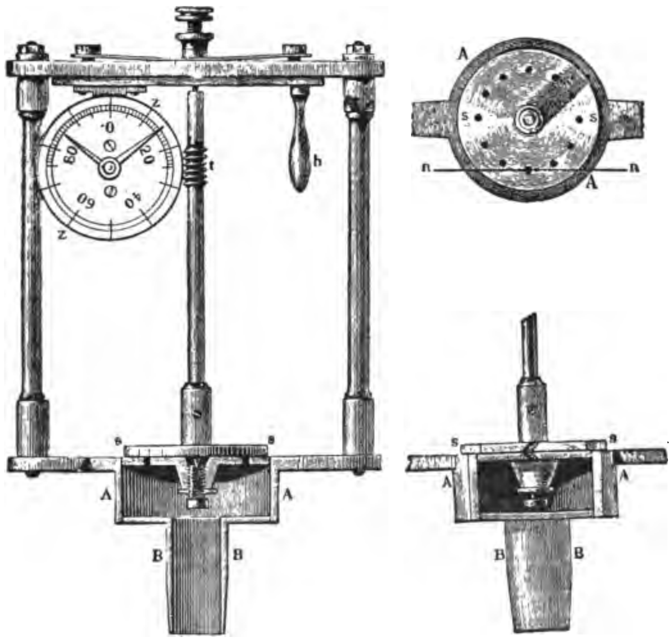


Fig. 19. Cagnaird-Latour's Siren.

entering through the tube *B B*, is forced in puffs that are emitted simultaneously from all the holes, whenever these coincide. Thus if there be twelve holes, as in the drawing, evidently twelve of these combined puffs must occur at each revolution of the disk. The holes are cut slant-wise in opposite directions, as shown in the lower right-hand drawing, which is a section through *n n* in the upper right-hand figure. By this means the stream of air is made to turn the disk, as well as to produce the sound-puffs. A screw thread *t* moves a mechanism which registers the results on a dial *z z*.

When the instrument is set in motion, the disk, revolving

slowly at first, gives out a series of detached puffs. As these quicken, however, a low sound is heard, which rapidly rises in pitch. To test the number of vibrations of any other sounding body, therefore, the siren must be made to give out a constant tone, in unison with the one that is tested, just as was the case with Savart's wheel; and the frequency is then announced on the dial. With both of these instruments, however, the difficulty consists in keeping a given pitch constant, since the slightest deviation from this constantly vitiates the results. Helmholtz partly remedied this defect by using an electric motor to run the siren, in place of the irregular wind supply.

Use of the siren.

Difficulties in connection with it.

A graphic method, which is capable of giving very accurate results, employs a style attached to a tuning-fork, as in Fig. 3 (page 3), except that the tuning-fork is made to write its story upon a revolving drum *T T*, shown in Fig. 20. This drum is turned by the shaft *A b*. After the drum has thus been kept in motion for a

The graphic method.

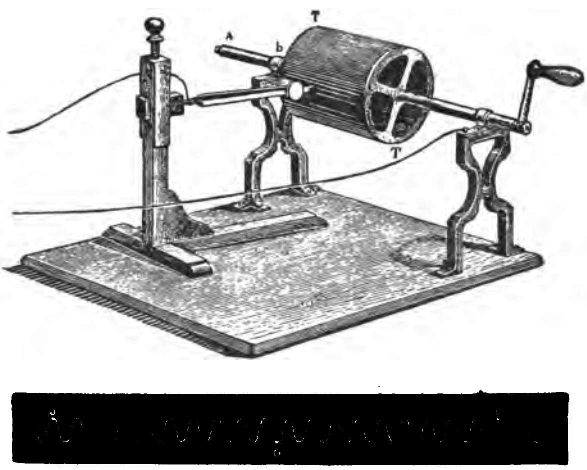


Fig. 20.

given time, say two seconds, the number of vibrations recorded during this time may easily be counted.

Scheibler's tonometer.

Scheibler (1777-1837) made an instrument called the *tonometer,* consisting of a series of tuning-forks the vibrations of which differ by a small and equal number, through the compass of an octave. In order to test a given pitch by means of this, it is only necessary to compare it with the tuning-fork nearest in unison with it. Koenig afterward constructed on this plan a *grand tonomètre universal,* which covered the entire range of audible sounds, and involved a hundred and fifty tuning-forks, adjusted with the utmost nicety, of which the largest were five feet in length.

Other methods.

These represent only a few of the devices used in pitch-measurement. Others include modifications of these, and instruments constructed on different lines, such as those involving strings (page 33). With these varied means for verifying results, it is evident that pitch can be calculated to a high degree of minuteness.

The limits of audibility—grave tones.

As to the exact limits of audible sounds, scientists are not fully agreed. Some assert that the limit of grave sounds is fifteen or sixteen vibrations per second. Helmholtz, however, contended that no true tone is produced by vibrations of less frequency than thirty per second; and it is probable that this view is correct, although for practical purposes the theoretical limit of sixteen is frequently assumed. To some ears, moreover, sounds are perceptible at a lower limit than to others; and, also, the difference in the composition of the sounding body may cause a difference in the number of vibrations necessary to blend into a tone.

Measurement of acute sounds.

Of acute sounds, the limits of audibility are much more difficult to fix. It is asserted that sounds of which the vibration number is as high as 38,000 per second have been heard; but for most persons the limit is about 16,000 vibrations. For the measurement of very

high pitches the whistle shown in Fig. 21 has been devised, which is capable of adjustment to the slightest variation in acute pitch. The air is forced into this by the rubber bulb, and, by means of a scale attached to the whistle, the vibrating column of air in the tube can be shortened as minutely as 1/250th of an inch.

Fig. 21.

Young people are, in general, capable of hearing sounds of a much higher pitch than is perceptible to those of maturer years. Likewise the degree of susceptibility to different pitches varies largely with individuals. Very high or very low sounds are harder to differentiate than those of medium pitch. Sometimes even the trained ears of a piano tuner are incapable of adjusting the pitches of the notes in the uppermost octave with accuracy. Occasionally, also, we discover a "tone-deaf" person, who finds difficulty in distinguishing between contiguous sounds in the middle musical register, especially if these be given out by a non-sustaining instrument, like the piano. Such obtuseness to pitch may generally be remedied, in part at least, by sufficient cultivation, especially in early youth: a result which speaks for the desirability of ear-training courses in our schools.

Differences in susceptibility to pitch.

To a few individuals is given the faculty of what is called "absolute pitch," which means the power of immediately recognizing the place in the scale of any sound heard. *Prima facie,* one possessing this gift should have other qualities of a musician: although this result does not always follow, just as absolute pitch is not by any means an universal or even a common possession of musicians.

Absolute pitch.

Since our system of notation employs the same letters, from *A* to *G* inclusive, for each octave, it is necessary to indicate more specifically which octave is meant when one of these letters is designated. Scientists use the signs

Distinguishing names of the octaves.

C_{-2}, C_{-1}, C_1, C_2, C_3, C_4, C_5, C_6, C_7, &c.,

of which C_4 is the treble C , and the others are the C's in both directions from this, at octave distances. A system more commonly employed by musicians, and the one which we shall use in our discussions, designates the scale notes as follows:

Still lower octaves are indicated by adding figures below the capital letters (C_1, C_{11}), and higher ones by adding to those above the small letters (c^{iv}, c^v, &c.).

As pitch can be measured so accurately, one would expect that the advantages of an universal standard would cause the immediate adoption of such an one for all purposes. But the facts show quite contrary conditions, as will be understood by consulting the table on the opposite page, which indicates some of the fluctuations of the pitch-standard since the year 1300. *S* over the first column shows the rise in pitch from the ideal lowest in semitones and hundredths of semitones, while under *a'* in the second column are given the number of vibrations of *a'* in the stated cases. Owing chiefly to the desire of leaders of bands and orchestras to produce brilliant effects, the pitch has gradually risen from the time of Handel and Mozart, so that now singers are compelled to render compositions of that period more than a semitone higher than was originally intended, to the disadvantage of both singer and composition.

Fluctuating pitch-standards.

A number of attempts have been made in recent years to secure uniformity. As the result of several conventions of piano and organ manufacturers, most of these instruments are now tuned to the so-called *International Pitch*, identical with the French *Diapason normal*

Modern standards.

TABLE OF HISTORICAL PITCHES, FROM LOWEST TO HIGHEST

S	a′	Date	Particulars.	Character.
0.00	370.	....	Ideal lowest, or zero point.	Lowest church pitch.
.19	374.2	1700	Lille, organ of L'Hospice Comtesse.	
.31	376.6	1766	Paris, from model after Bédos.	
1.04	393.2	1713	Great organ in Strassburg cathedral.	Low church pitch.
1.14	395.2	1759	Organ at Trinity College, Cambridge, England.	
1.29	398.7	1854	Lille, restored organ of La Madeleine.	
1.48	402.9	1648	Paris, Mersenne's spinet.	Low chamber pitch.
1.74	409.	1783	Paris, court clavecins.	
1.96	414.4	1776	Breslau, clavichords.	
1.99	415.	1754	Dresden, Silbermann organ.	Mean pitch of Europe.
2.26	421.6	1780	Vienna, Stein pianos, used by Mozart.	
2.30	422.5	1751	England, Handel's tuning fork.	
2.33	423.2	1815	Band of Dresden opera, under von Weber.	
2.48	427.	1811	Paris, Grand Opera.	
2.51	427.8	1788	England, St. George's Chapel, Windsor.	
2.72	433.	1820	London Philharmonic.	Compromise pitch.
2.82	435.4	1859	Paris, *Diapason normal* of Conservatoire.	
3.01	440.2	1834	Scheibler's "Stuttgart Standard."	Modern orchestral pitch and medium church pitch.
3.07	441.7	1690	Organ at Hampton Court Palace, England.	
3.16	444.2	1880	United States, "low organ pitch."	
3.22	445.6	1879	London, Covent Garden Opera.	
3.33	448.4	1857	Berlin Opera.	
3.45	451.7	1880	United States, Chickering's standard fork.	
3.69	458.	1880	United States, Steinway's pitch.	
4.29	474.1	1708	London, Chapel Royal, St. James.	High church pitch.
4.84	484.2	1688	Hamburg, St. Jacobi Kirche, approved by Bach.	
5.34	503.7	1636	Paris Mersenne's *ton de chapelle.*	Highest pitches.
7.26	563.1	1636	Paris, Mersenne's chamber pitch.	
7.40	567.3	1619	North German church pitch.	

of 1859, which has a'=435. Modern orchestras and military bands, however, generally employ the higher *Scheibler Stuttgart* pitch of 1834, by which a' has 440 vibrations. Physicists, for the sake of ease in computations, take as pitch-basis the theoretical limit of audibility, giving C =16 vibrations, so that C_1=32, C=64, c=128, and c'=256 vibrations. From these figures a'=426.6, a standard considerably lower than either of those just cited.

The musical compass.

In the earlier centuries of the Christian era, when music was almost exclusively vocal, the tones employed were restricted to fifteen or twenty, arranged diatonically in the middle register (page 94). With the advent of chromatic notes, however, and with the greater latitude which followed the extended use of instruments, the compass rapidly increased until it finally embraced all the tones from the limit of audibility in the direction of grave sounds to those sounds which are so piercingly acute as to be unavailable for artistic purposes. The piano now begins with A_{II} of about 27½ vibrations, and continues to c^{V} of 4224 vibrations. In the orchestra the lowest note, rendered by the contra-bassoon, is C_1 of about 33 vibrations, while the highest is d^{V} of the piccolo, with 4752 vibrations.

Influence on pitch of wind and intensity.

Allusion has been made to the influence of wind upon sound-velocity. While the sound-waves are pushed forward by the wind when both are travelling in the same direction, the resultant pitch is not affected, as might be expected, since the sound-waves are at the same time elongated so that eventually the same number reach the ear in a given time as would do so under normal conditions. Likewise the intensity of sounds has no effect whatever on their pitch, for otherwise the music of a band, produced by instruments of varying strength of tone, would sound hopelessly out of tune.

If, however, the distance between a sounding body and the listener varies rapidly, a perceptible alteration in pitch results, since, when the object is approaching, the sound-waves are

crowded together, and when it is receding, the number which reach the listener in a given time is correspondingly reduced. Thus the whistle of an engine becomes more acute when the train rushes towards us, and falls gradually, after it has passed.

Influence of a rapid change of position upon pitch.

Instrument makers must take into account the laws which govern pitch, in order to utilize their materials to the best advantage. For the study of such laws, an instrument called the *sonometer* is especially valuable. Pythagoras, the Greek philosopher, used this under the name of *monochord,* or *instrument of a single string;* and from his time to the present, scientists have found it one of the most available means of investigating tonal relations. In its modern form (Fig. 22) it consists of a long resonant box of fir, *M N,* over which are stretched two wires. One of these *a d* is attached to a pin at each end, and can be regulated in its tension by a piano key, *p*. The second string, *b R,* is fixed at one end only, since the other, passing over the pulley *R,* is stretched by a weight at *P*. The bridges *B* and *B'* are stationary, while the bridge *C* moves upon a scale divided into millimeters.

The laws of pitch.
The sonometer.

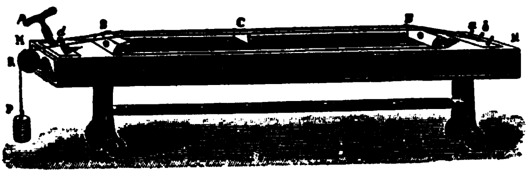


Fig. 22. Sonometer.

If the bridge *C* be removed, and one of the strings be plucked in the middle, it will vibrate in its entire length, and give out a fundamental tone. Let the bridge be now inserted so that the string is divided into two equal parts. Each of these will give a tone an octave above the original, and will vibrate twice as fast. In like manner, if the string be divided into three equal portions, each of these will vibrate three times as fast as the entire string; and one of four equal portions will have four times the original vibration number. Thus the number of vibrations

Laws of strings.
1. That concerning the length.

increases in exact proportion as the string is shortened, or, in mathematical terms, **the number of vibrations is in inverse proportion to the length of the string.**

Let us next make the weight P equal to one pound, and ascertain the vibration number of $b\ R$ at this tension. If we then increase the weight until this vibration number is doubled, we shall find the weight equal to four pounds. Likewise to treble the original vibration number requires a weight of nine pounds, and to quadruple it one of sixteen pounds. Therefore, the weight must equal in pounds not the number by which the original vibrations have been multiplied, but the *square* of that number. Thus two times the original number of vibrations is produced by a weight 2×2 the original one, three times the original vibration number by a weight 3×3 the original one, and so forth. Hence, conversely stated, **the number of vibrations per second of a string varies directly as the square root of its tension.**

2. That concerning the tension.

Again, if the two strings of the sonometer be given the same length and tension, and one is twice as thick as the other, the latter will vibrate twice as fast as its companion; and, in general, any increase in thickness occasions a corresponding decrease in the vibration number. Thus we may assert that **the number of vibrations of a string varies in inverse proportion to its thickness.**

3. That concerning the thickness.

Upon these three laws is based the construction of all stringed instruments. In those like the violin, where the strings are few and the tension-strain is not great, strings all of the same length are used, while their pitch is regulated by their thickness and tension. In the many-stringed piano and harp, however, the strain is made more nearly equal by shortening the strings as they ascend in acuteness, as well as by diminishing their thickness. Thus the short fine wire of the high tones is replaced in the lower ones by a heavy wire several feet in length and further weighted by an encircling wire-coil.

Observance of these laws in instrument making.

The instrument maker must also remember that the laws of strings apply strictly only to the ideal string defined by physicists as "a perfectly uniform and flexible filiment of solid matter stretched between two fixed points." As there are always imperfections in actual strings, especially in the direction of stiffness and lack of uniformity, the laws must be somewhat modified to suit these existing conditions. Thus, when a string is divided into two equal parts, each of these will be found a trifle flatter than it should be theoretically.

Modifications of these laws.

Other sounding bodies are subject to laws sometimes quite different from those regulating the pitch of strings. With rods, the pitch rises very rapidly as the vibrating part is shortened, so that **the number of vibrations is inversely proportional to the square of the length of the vibrating part.** Tubes are subject to conditions more nearly like those governing strings, since **the pitch of the air-vibrations in the tube varies inversely as the length of the tube.** A fuller discussion of these laws is reserved for a following chapter.

The pitch of vibrating rods and tubes.

SUMMARY

SOUNDS differ chiefly in respect to their pitch, loudness and quality.

Pitch depends upon the number of vibrations which a sounding body performs in a given time.

The vibration number per second of a sounding body is calculated in various ways, such as by Savart's wheel, Latour's siren, the graphic method, and the tonometer.

Sounds are audible for something over eleven octaves, or from 16 to 38,000 vibrations per second, although the sense of pitch varies much with different persons. Of these sounds only those of between 16 and 4800 vibrations are used in music.

Standards of pitch have varied greatly at different times and for different purposes. Even now there are several standards in use.

Pitch is unaffected by wind or loudness, but varies somewhat when a sounding object rapidly approaches or recedes from the listener.

Instruments are constructed in accordance with the laws of pitch, which have been ascertained with regard to the various kinds of sounding bodies. Those governing strings depend on the length, tension and thickness of the string.

REFERENCE LIST.

Helmholtz, Chapter 1.
Harris, Chapters 4, 9.
Taylor, Chapter 2.
Zahm, Chapters 2, 4.
Lavignac, Chapter 1, A.
Stone, Chapter 4.
Tyndall, Chapters 2, 3.
Broadhouse, Chapters 5, 9, Appendix C.
Poynting and Thompson, Chapters 3, 6.
Barnes, Chapters 5, 3.
Barton, Chapters 1, 10.
Blaserna, Chapter 4.
Catchpool, Chapter 7.
Pole, Chapter 3.

CHAPTER IV

LOUDNESS, INTERFERENCE, AND RESULTANT TONES

THAT the loudness with which a sound strikes our ears is intimately associated with the degree of energy with which the sounding body is vibrating is a matter of common observation. Pluck a violin string gently, and the tone which results is weak. Pluck it harder, so that it oscillates violently from side to side, and a strong tone is heard. Again, strike a tuning-fork lightly, and observe the weakness of the tone which it gives out. A harder stroke, imparting added energy to the vibrations, will greatly increase the sound-power. By a slight modification of the experiment shown in Fig. 3, the relation between the extent of vibration and the strength of tone can plainly be seen. Let the smoked glass be pulled slowly along, after the tuning-fork has been agitated, until, decreasing gradually in loudness, the tone ceases altogether. A narrowing white space on the glass is the result, as exhibited in Fig. 23, which demonstrates that the width of the vibrations gradually diminishes as the tone lessens. The width of vibration is called its *amplitude;* and physicists have formulated the law that **the strength of the sound varies according to the square of the amplitude.** Thus in the case of two tuning-forks A and B, of the same pitch, if A vibrates with an amplitude of one-fifth of an inch and B with that of one-tenth of an inch, the sound of A will be four times as loud as that of B, since it vibrates through twice the distance.

Relation of intensity to amplitude.

Fig. 23.

It has also been found that sound-vibrations are subject to

the law which governs the vibrations of a pendulum, namely, that within ordinary limits the number of vibrations continues the same, whatever be the extent of the swing. Hence, **increase or decrease in the amplitude of vibration of a sounding body does not affect its pitch, since the number of vibrations remains constant.**

Amplitude and pitch.

In free air, the vibrations proceed from the sounding body in the form of an enlarging sphere. Mathematicians have determined that the mass of air included within a yard's radius from the centre of a sphere is only one-fourth of that included within a two yards' radius, and one-ninth of that within a three yards' radius. Hence, the sound-vibrations in traveling two yards from their origin must spread over four times the territory which they cover in the first yard alone, nine times the latter amount in travelling three yards, sixteen times in travelling four yards, and so on. A person at *C*, therefore (Fig. 24), twice as far away as a person at *B* from the source of sound at *A*, will hear the sound only one-fourth as loud, since it will have spread over four times the space. Stated as a law, then, **the intensity of a sound in free air diminishes as the square of the distance of the listener from the sounding body.***

Distance and intensity.

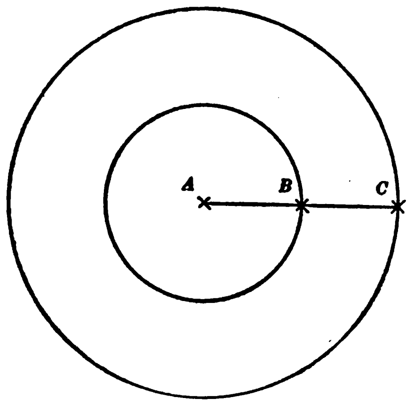


Fig. 24.

*The difference in meaning between the words *intensity* and *loudness* should be noted. *Intensity* refers to the energy of the sound-vibrations—a physical, measurable quantity, while *loudness* refers to the sensation which the listener derives from the auditory nerve after this energy has been communicated to it. Intensity and loudness are therefore related as cause and effect.

Actually, however, the effects of this law are much modified by disturbing elements. Striking other objects, sounds are echoed or reinforced (page 19), and, when they originate near the earth, half of the sphere in which the sound-waves tend to travel is evidently intercepted by the ground. The more the territory over which they are allowed to spread is contracted by such means, the less does their intensity diminish; and when they are confined to a tube, they may travel for long distances with little loss of intensity, since their force is expended only slightly by friction along the walls of the tube and by the amount imparted to these walls. The French physicist Regnault (1810-1878), in experiments conducted through the Paris sewers, was able to hear a pistol shot distinctly for a distance of six miles when these sewers were made to act as a sound-carrying tube. Speaking tubes furnish an illustration of one of the practical uses to which this principle has been put.

Sound-waves confined to a tube.

Since the impact of the air-particles is more direct as the air becomes denser, sound is then carried by them with greater intensity; and, conversely, as the air becomes rarefied, its intensity is lessened. In very rarefied regions, such as the tops of high mountains, the modification of intensity is so decided that the report of a pistol sounds scarcely louder than that of a fire-cracker under ordinary circumstances.

Density and intensity.

As a general rule, sounds are heard with more distinctness at night. This phenomenon is only partly accounted for by the absence of confusing noises audible in the daytime, and is probably due in a still larger measure to the fact that the air is in a more homogeneous condition at night, since the conflicting heat currents induced by the sun (page 20) do not then exist.

Sounds louder at night.

Why the intensity of a sound is greater in the direction in which the wind is blowing has been a matter of considerable speculation. Perhaps the most plausible theory is the one which asserts that, as the air blown along by the wind is retarded by friction where it touches the

Effect of wind upon intensity.

earth, the sound-waves are bent downward, striking the listener with greater force. On the other side of the sounding body the reverse process must take place, since the lower parts of the sound-waves are less antagonized by the wind than the upper parts, and the waves are consequently bent upward, thus becoming weaker near the earth. In Fig. 25 is shown the action

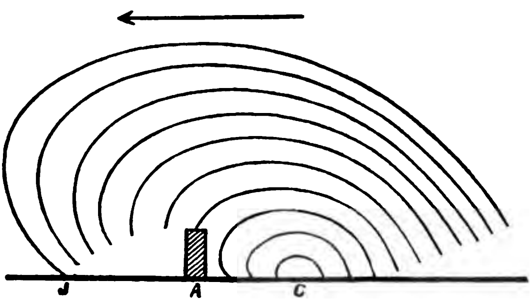


Fig. 25.

of the wind, which blows in the direction of the arrow, bending down the sound-waves from the vibrating body *C* in the direction of *J* and inclining them upward in the opposite direction. Every intervening object, such as that at *A* tends to increase the downward slope toward *J*.

Resonance and intensity.

Sound-intensity is also much affected by the sympathetic vibrations of bodies other than the one by which the sound is produced. This phenomenon is discussed in Chapter VI.

Nature of the phenomena of interference.

Having considered the intensity of single sounds, let us now inquire how this intensity is affected when our original sound-waves come into contact with those arising from other sources. A very striking example of what then happens is afforded by the action of water-waves. If we observe the ruffled surface of a lake, we perceive a great variety of waves, the smaller superimposed on the larger in the form of ripples, those encountering others in their path passing over their convolutions, but *each set of waves preserving its identity so long as its energy lasts.* In

the same way the condensations and rarefactions of different sound-waves pass through those of other waves which they encounter, each keeping its distinctive character throughout. Finally, the ear has a wonderful power of selecting out the sound-waves which have periodic vibrations, and the mind, having perceived these varieties of wave-frequencies, proceeds to assign them to their respective causes with a considerable degree of accuracy. Hence, hearing a multitude of sounds at the same time, the hum of bees, the monotone of a waterfall, the rustle of the leaves, the lowing of a cow, the barking of a dog, we are able to distinguish between all of them, and to form judgments as to the character of their origins. Very loud sounds may, of course, blot out very soft ones. But even in the case of great disparity in intensity, slight sounds are sometimes perceptible, on account of their distinctive quality. Thus a device for attracting the attention of an individual in the midst of the roar of mill machinery is to produce a light hissing sound between the teeth. The various results which arise from the meeting of different sound-waves are classed under the head of the *phenomena of interference.*

Interference of sounds of the same pitch.

What happens now, when two sounds encounter which have the same vibration numbers? This phenomenon has already been noticed in connection with sound-reflection (page 20). Let us assume that two tuning-forks having the same pitch are sounding at a short distance from one another. When their waves meet, one of

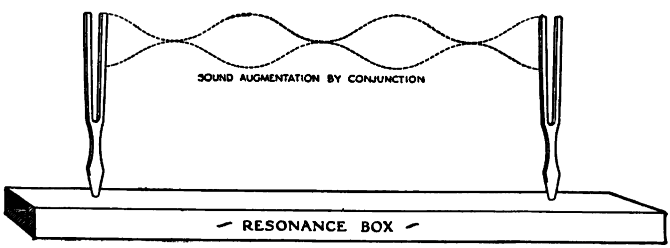


Fig. 26.

three results must follow: the condensations from the one fork may be added to those from the other and the rarefactions from the one to those from the other, in which case the sound is greatly augmented (Fig. 26); the condensations from one fork may be imposed upon the rarefactions from the other

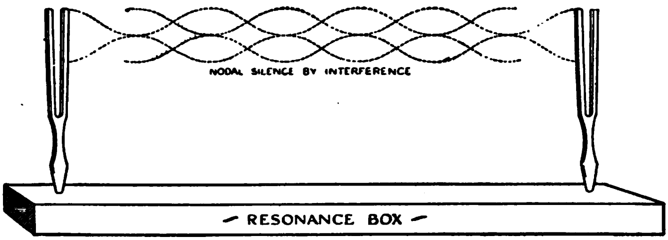


Fig. 27.

(Fig. 27), in which case they neutralize each other, and the sound is nearly extinguished; or, as is most frequent, the waves may meet irregularly, at some point between those mentioned in the first two cases, when the intensity may vary either one way or another, according to the point of contact.

Interference illustrated by a tuning-fork.

This effect of sound-interference is easily demonstrated by holding a sounding tuning-fork parallel to one ear, while the other is stopped by the finger. If now the fork be slowly rotated, four points will occur in the course of a revolution where the sound is extinguished. The reason for these silences is explained when we reflect that at each time the prongs of the fork vibrate outward they not only form a condensation by their impact, but also leave behind a corresponding rarefaction, in the space between them. Similarly, on their opposite swing, they form a condensation in the central space while a rarefaction is left in the outside air. Two sets of vibra-

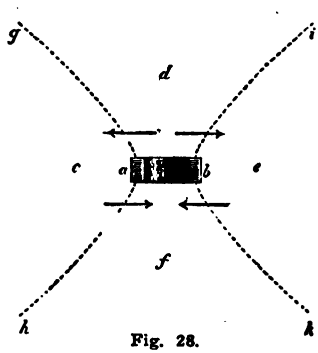


Fig. 28.

tions are thus propagated, having the same frequency but opposite phases; and the waves thus generated meet along the lines extending out from the four corners. In Fig. 28 we are supposed to look down upon the ends of the prongs *a b*, which vibrate outward and inward as represented by the arrows. The sound will be strong at *c d e* and *f*, but will be quenched along the lines *g h i k*, where the waves neutralize each other.

Experiment with metal plates.

Metal plates, known as Chladni's plates (page 61), tend to divide up, when sounding, into several equal sectors, of which those adjacent to each other give out sound-waves of opposite phases, that is, one is producing condensations while the other is producing rarefactions, and *vice versa*, although their vibration numbers are the same. If a forked tube *C D E* (Fig. 29), capped by a membrane on which sand is strewn, be placed with one of its prongs over each of two alternate sectors *A A* or *B B*, the sand will be violently agitated, owing to sympathetic resonance (page 69); but if the prongs be placed over adjacent sectors *A B*, as in the drawing, the sand will remain undisturbed, showing that the two sets of vibrations are mutually destructive.

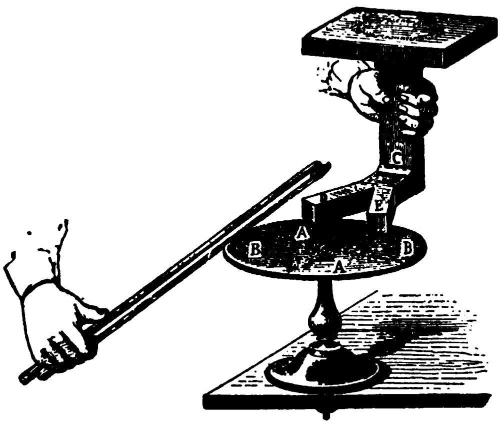


Fig. 29.

Again, if two organ pipes of equal dimensions be fed from the same wind-chest, they will vibrate in opposite phases, and

their sounds, instead of being reinforced, will be nearly extinguished. Organ builders are obliged to guard against this contingency, in constructing their instruments.

Experiment with organ pipes.

Having discussed the results which occur when two equal sounds having the same vibration number come into conflict, let us now consider what happens when these two sounds have different vibration numbers. Suppose that two sets of vibrations *D* and *E* are travelling in the same direction, starting in opposite phases, so that the first vibration of *D* is neutralized by that of *E*. If, now, *E* be travelling faster than *D*, it will gradually gain upon *D* until a condensation pulse of *E* corresponds with one of *D*. Still gaining on *D*, *E* now passes along until the vibrations are again in opposite phases, and the sound becomes again inaudible. At this point *D* will have made an entire vibration more than *E*, and the sound will have grown from

Interference of sounds of different pitches.

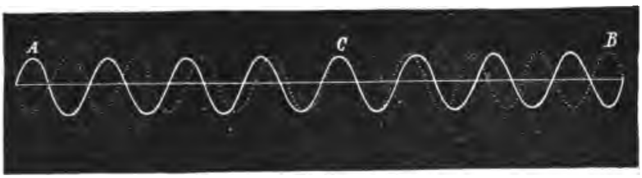


Fig. 30.

zero to a climax and then have diminished to zero again. Fig. 30 illustrates this process. Here *D* is represented by the dotted line, and *E* by the connected line. The opposing phases are at *A* and *B*, and the climax of intensity at *C*.

Such an increase and decrease of sound has been given the name of a *beat;* and it is evident that **one of these beats must occur whenever one set of sound-waves gains over another by a single vibration.** Thus if a sound vibrating 100 times per second travels with one which vibrates 101 times in the same interval, one beat per second will result; if the first sound vibrates 100 times while the

Beats and their frequency.

second vibrates 102 times, there will be two beats; and so on. Given the vibration number of one sound, therefore, it is easy to determine that of another which vibrates nearly in unison with it, simply by counting the number of beats per second which they cause when sounding together, and adding or subtracting these from the vibration number of the first sound, according as the second sound is sharper or flatter. It is on this principle that the vibration numbers of sounds are reckoned from the tonometer (page 28). Tuners of instruments, also, gauge the accuracy of their work by noting the beats. A piano tuner, for instance, adjusts a string so that no beats occur between it and the tuning-fork with which it should be in unison. As there are generally three strings to each tone, the other two strings are then stretched until they make no beats with the initial string, when their unison with it must be perfect.

The result of quick beats.

As the difference between the vibration numbers of two sounds increases, the beats quicken until they blend together, just as the spokes become indistinguishable when a wheel revolves quickly. The effect of unrest remains up to a certain point, however, voicing itself in what is commonly called a *discord* between the two tones (page 98).

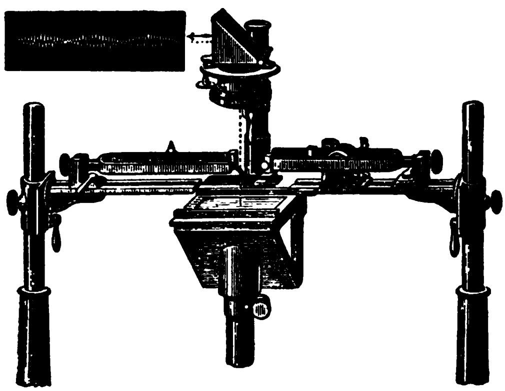


Fig. 31.

Lissajous' apparatus for recording beats.

Lissajous (1822-1880) devised an apparatus by which the combined results of the vibrations of the two tuning-forks could be thrown upon a screen. An improved form of this is shown in Fig. 31. Of two tuning-forks *A* and *B*, one is kept sounding by means of an electric current, while the number of vibrations of the other is regulated by a sliding weight on one of its prongs. By means of a style attached to the end of each fork, the combined vibrations are recorded on a smoked-glass plate,

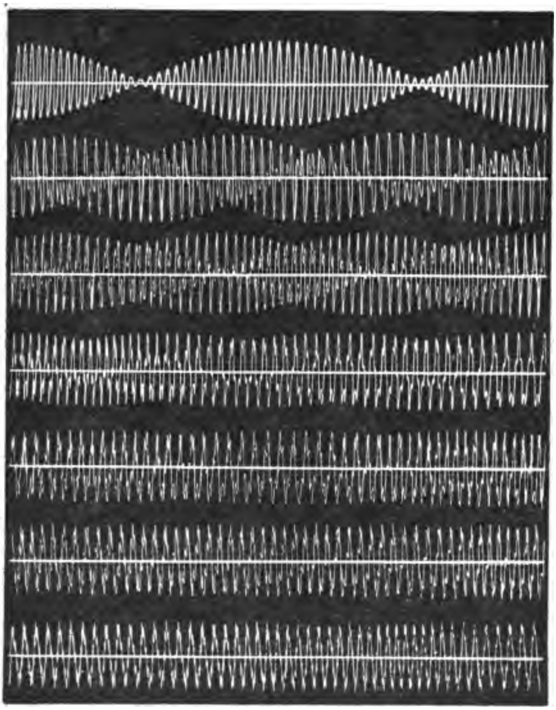


Fig. 32.

and thrown upon a screen by the lantern at the top of the apparatus. Dr. Koenig, using a similar device, obtained the results shown in Fig. 32.

Many other conditions beside those described may give rise to beats. Defects in a musical instrument, causing its parts to vibrate out of unison, may produce them: thus we often hear beats in the tone of a bell, owing to the fact that it divides into segments when sounding and that these segments have imperfections in construction which puts them slightly out of tune with each other.

Beats occasioned by defects in instruments.

Beats are produced not only by the fundamental tones, but also by the *upper partials* or *overtones* which accompany them in most musical sounds (page 51), when these overtones differ from one another slightly in pitch. Accordingly, the interference of two complex tones may involve a variety of beats of different degrees of loudness and of rapidity.

Beats from overtones.

When we hear two loud tones of different pitches sounding together, we are sometimes conscious of the presence of a third tone, lower in pitch than either of them. Tartini (1692-1770), the noted violinist, is said to have first drawn attention to the existence of such tones, and in his honor they were formerly called *Tartini's tones,* although they are now generally known as *resultant tones*. The following table shows in black notes the resultant tones produced by the chief intervals included within the diatonic scale, represented by white notes on the upper staff (Fig. 33):—

Resultant tones.

Fig. 33.

Perhaps the reed organ is the best available instrument with which to experiment with resultant tones. They are not always easily perceptible; but if the tone of the same pitch as the resultant tone be previously sounded, the latter can be more readily detected when its generators are played.

How to hear these tones.

What causes these tones is still a matter of controversy. Since the vibration number of a resultant tone was found to

Helmholtz's theory of resultant tones.

be equal to the difference between the vibration numbers of the generating tones, and is therefore of the same frequency as the beats which they produce, it was at first supposed that the resultant tones were caused by these beats. Helmholtz, however, discredited this theory on the ground that the resultant tones and the beats were sometimes heard simultaneously; and he therefore advanced the theory that when the amplitudes of the vibrations of two sounds are very great these set in motion other sound-waves, different from either of the original ones. From this theory he also deduced the existence of what he called *summational tones,* whose vibration numbers are equal to the sum of those of their generators. What we have described as resultant tones he distinguished as *differential tones.*

Dr. Koenig, however, as the result of many intricate experiments, reverted to the former theory, renaming resultant tones

Dr. Koenig's theory.

beat-tones. In support of this theory he not only proved that a tone and the rattle of the vibrations which produces it can sometimes be heard simultaneously, but also showed that many of the phenomena connected with resultant tones are explainable only on the hypothesis that they are caused by the beats. It is also a matter of dispute as to whether these tones really exist in the outside air or are formed within the cavity of the ear itself, Helmholtz advocating the former view and Dr. Koenig the latter.

SUMMARY

THE loudness of a sound is proportional to the square of the amplitude of its vibrations. Variation in this amplitude does not affect the pitch.

In free air, sound-intensity is inversely proportional to the square of the distance of the listener from the sounding body. When sound is restricted to the boundaries of a tube, however, it proceeds with little lessening of intensity.

Sounds are louder in dense than in rarefied media, and are also generally louder at night. They are intensified in the direction in which wind is blowing, and softened in the contrary direction.

The results which follow when two sets of sound-waves meet are called the phenomena of interference.

When two sounds of unison pitch and equal intensity meet, the individual intensity of each may be augmented up to twice what it was at first, or it may be reduced even to complete extinction.

If the two sounds are not in unison, undulations in intensity known as beats occur, of which the number per second equals the difference between the vibration numbers of the sounds. Various conditions give rise to beats. They are useful for determining exact vibration numbers.

Two loud sounds are sometimes accompanied by a resultant tone, the nature of which is disputed by physicists.

REFERENCE LIST.

Helmholtz, Chapters 2, 4, 7, 11.
Tyndall, Chapters 1, 8, 9.
Zahm, Chapters 2, 7.
Harris, Chapters 6, 12, 13.
Catchpool, Chapters 4, 8.
Taylor, Chapter 2.
Poynting and Thompson, Chapters 1, 10.
Stone, Chapters 3, 5.
Broadhouse, Chapters 5, 12, 14.
Blaserna, Chapters 2, 5.

Meyer, Chapters 8, 13, 14.
Barnes, Chapters 9, 12.
Barton, Chapters 1, 7.
Pole, Chapter 3.

CHAPTER V

Quality

The third property of sound, that of *quality*, enables us to distinguish between sounds even if they be of the same pitch and equal loudness. In listening to an orchestra, for instance, we recognize without difficulty the tones produced by the violins, the flutes, the oboes and the trumpets by the characteristic quality of each. We are also able to draw distinctions between two instruments of the same species, saying of two violins that the one is smooth and pleasant in tone while the other is rough and disagreeable. Again, under the fingers of an artist a violin may give out melodious and thrilling tones, while the same instrument constantly offends our ears when handled by an unskilled amateur. There are thus unlimited gradations in tone-character: gradations which are so analogous to shades of color that they are often spoken of by musicians as *varieties of tone-color*.

Characteristics of quality.

Scientists for a long time found much difficulty in explaining the phenomena of sound-quality. Joseph Sauveur (1653-1716), the inventor of the word "acoustics," and several others advanced the theory that quality is produced by the combination of secondary sounds with the chief tone; but no adequate development of this idea was presented until Helmholtz brought out his authoritative work, which contained a full and conclusive study of the subject. In this he clearly proved that **almost every musical tone consists not only of a principal tone, but also of a number of subordinate tones of lesser intensity.**

Theories as to the nature of quality.

To these secondary tones several names such as *overtones* and *harmonics* have been given. The latter term was applied by Sauveur on the theory that the numerical relations which their vibrations bore to those of the principal tone could always be expressed by whole numbers

Use of the term "partials."

in the series 2, 3, 4 and so on. It has since been discovered, however, that in many instances, notably in connection with rods, bells and plates, these relations are much more complex than was at first suspected. A more comprehensive nomenclature, therefore, designates all the tones which combine to produce the total effect from a single sounding body *partials.* The lowest of these, which is generally also the most prominent, is the *fundamental,* while the others are *upper partials.* Those whose relations to the fundamental can be expressed in simple whole numbers are called *harmonic partials,* while the others are called *inharmonic partials.**

Laws governing the quality of a tone.

Helmholtz demonstrated the important law that **the character of an individual tone is determined by the number and position of the upper partials and their relative intensities.** Dr. Koenig afterward showed that quality was also affected by the relative positions of the condensations and rarefactions of the upper partials, or their difference in *phase.* It can readily be seen, therefore, that, since a multitude of combinations of the upper partials may occur with every variety of intensity and with still other modifications through variations in phase, there is practically no limit to the number of possible gradations in tone-quality.

Helmholtz's resonators.

A clever device called a *resonator* (Fig. 34) for detecting and studying upper partials was invented by Helmholtz. This is in the form of a hollow globe best made of thin brass, having a small aperture *b* on one side with a projection which can be inserted

Fig. 34. Helmholtz's Resonator

*The reader should be careful not to confuse the terms *partials* and *upper partials,* the former name including both the upper partials and the fundamental. Thus the fundamental is the first partial, the first upper partial is the second partial, the second upper partial is the third partial, and so on.

in the ear, while a larger opening *a* in the opposite side admits the sound-waves from the outer air. In accordance with the principles of resonance explained in the next chapter, this instrument has the power of selecting out a single tone to which it is tuned and of reinforcing this tone so that it strikes the ear with greatly increased intensity. By constructing a number of these resonators tuned respectively to the various degrees of the scale, Helmholtz was able to listen for the appearance of upper partials in a given sound and to determine the pitch and intensity of any one of these by its agreement with the pitch of its sympathetic resonator.

Effect on a tone produced by adding partials.

In this manner it was discovered that only in a few instances, including mainly the tones produced by some tuning-forks and stopped organ pipes, was there an approach to an absolutely simple tone. Moreover such pure tones, while pleasant to hear, quickly become uninteresting. With the addition of simple harmonic partials, character and vitality is imparted to a tone; while an admixture of remote overtones results in more pungency and incisiveness, frequently accompanied by discordant elements. Unfortunately, the range of tone recognizable by the resonators does not extend to sounds very acute in pitch, so that it is difficult to investigate the character of the highest upper partials.

How far vowel sounds can be reproduced artificially.

While, therefore, it is comparatively easy to analyze the simple harmonic partials of a given tone, it is a more difficult task to reconstruct this tone if it contains partials beyond the reach of resonators. This fact has made the problem of reproducing the varieties of vowel sounds hard to solve. Helmholtz, Koenig and others, recognizing that the peculiar characteristics of spoken vowels are caused by certain combinations of upper partials, have made many attempts to mimic these sounds by artificial means. By sounding together tuning-forks of pitches and strengths corresponding to the ascertained values of the partials, an approach was made in some cases to the original sounds; but

owing to the impossibility of providing for many inharmonic partials outside the scope of the resonators, some of these experiments proved less successful. Fig. 35 depicts an elabo-

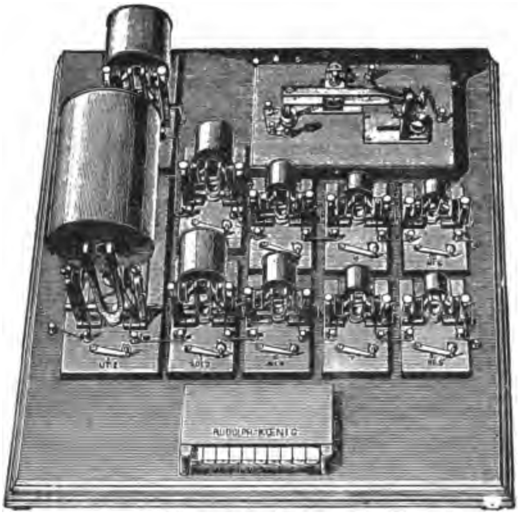
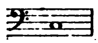


Fig. 35.

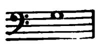
rate instrument made by Koenig, consisting of ten reinforced tuning-forks which can be put into vibration by means of an electric current. The keyboard in front allows the operator to throw on any combination of these forks which he wishes, regulating also at will their relative intensities. By means of this instrument the vowels *u* (as in *boot*), *o* (as in *no*), and *a* (as in *ah*) have been reproduced with considerable fidelity; but only a slight suggestion can be given of those vowel sounds which contain complex and acute partials, such as the sounds of *e* and *i*.

Production of partials from strings.

For the investigation of the harmonic partials the best medium is the *stretched string*, some of the laws of which we have already studied in Chapter III. Let us again refer to the sonometer shown on page 33. Having tuned one of the strings to bass

C , let us touch a feather to the middle of the string and pluck the string half way between the point touched and one of the ends. We now clearly hear the second partial, which is the note *c* , just an octave above the first partial or fundamental. This new tone is produced by each of the two equal parts into which the string is divided, and each of which, according to the laws of stretched strings (page 33), must be vibrating twice as fast as the whole string. Where the feather touches the string there is scarcely any motion at all. This point is named a *node*. At the middle of the *ventral segments,* as they are called, which occur on either side of the node, are the points of greatest motion. If the feather be removed from the string the latter will continue to vibrate in halves as long as its momentum lasts.

Nodes and ventral segments.

Likewise, damping the string at one-third of its length will divide it into three ventral segments separated by two nodes; and the third partial thus given out will be an octave and a fifth above the fundamental . Again, the fourth partial, made by dividing the string into quarters, will be one octave above the second , while the fifth partial, produced by a division into fifths, gives the note a major third above its predecessor . It should be observed that the two ends of the string in each case form two other nodes, in addition to those enumerated.

Other partials of strings.

An interesting experiment is performed by placing a number

of small bent pieces of paper or "riders" upon the string before it is sounded, red ones where the nodes should appear and blue ones on the ventral segments. When the string is put into vibration the blue riders will instantly be unhorsed, while the red ones will retain their position. This effect is shown in Fig. 36.

Experiment with "riders."

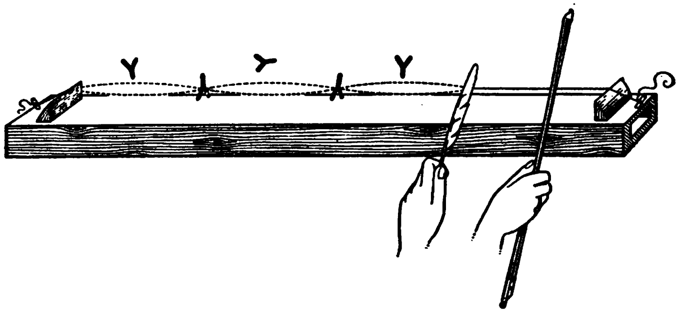


Fig. 36.

Continuing still further to divide up the string into integral parts, we may form any number of segments and their accompanying nodes. For practical uses, however, only a few of the harmonic partials need be considered. The first sixteen of these for the note *C* are shown in Fig. 37. The vibration numbers indicated beneath are calculated on the basis of the scientific pitch, which is somewhat lower than the international. Note also that the partials indicated by black notes are slightly out of tune with the corresponding tones in our scale.

The "harmonic series" of strings.

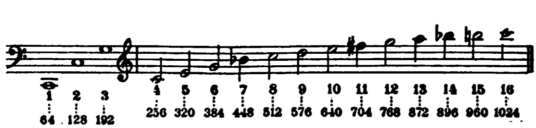


Fig. 37. The Harmonic Series

Let us now inquire what are the motions which a string

makes when the presence of several upper partials causes it to vibrate in a number of different directions at the same time. Fig 38 shows some of the simpler of these motions. If the string *A M B* gave out only its fundamental, it would assume the uniform curve *A C B*. When, however, the string, besides vibrating as a whole, also divides up into segments, these must adapt themselves to the fundamental vibration, appearing as alternate elevations and depressions along the length of the string.

Complex motions of strings.

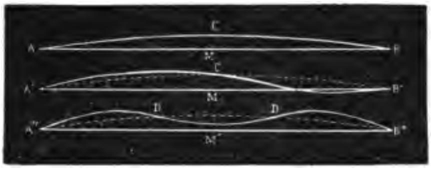


Fig. 38.

Thus when *A′ M′ B′* vibrates in its entirety and also in halves, the segment on one side moves outward when that on the other side moves inward, and *vice versa,* so that positions like *A′ C′ B′* are assumed. Again, *A″ M″ B″*, sounding its fundamental plus the second upper partial, takes positions corresponding to the curve *A″ D D′ B″*. As other overtones are added, the motions increase in complexity, each partial, however, preserving its individuality. This complexity is, of course, transferred to the resulting sound-waves, in which the various condensations and rarefactions are correspondingly superimposed upon each other.

Given upper partials, however, can exist only when conditions are favorable for the formation of their nodes and ventral segments. If, for instance, a string be plucked at its centre, there must be a maximum of vibration at this point and hence it cannot become a node. Consequently all the partials, such as the second, fourth and eighth, which have a node at the centre, are absent. Again, sounding a string at a point where the node of a discordant partial would be formed, the tone becomes more agreeable by the elimination of such partial. Hence the skilled violinist draws his bow at the most favorable division

Conditions under which given partials can occur.

of the strings, and the piano maker carefully disposes his hammer strokes to produce the best tonal quality.

Partials of rods fixed at one end.

The vibrations of bodies other than strings are governed by more or less divergent conditions. Turning to the subject of *sounding rods,* let us first examine the motions of a rod fixed at one end and free at the other. In Fig. 39 a rod thus located oscillates as a whole between the positions indicated by the dotted lines *p o* and *p′ o*. With

Fig. 39.

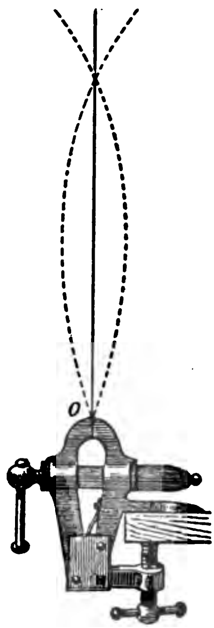


Fig. 40.

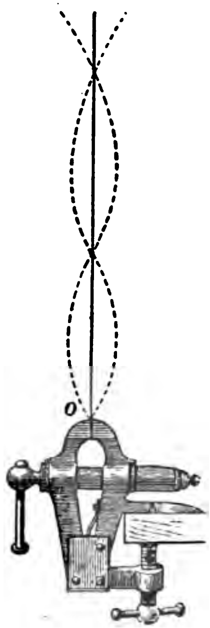


Fig. 41.

the advent of the second partial the fixed end must form a node, but the free end, unrestricted in its motion, becomes the centre of a ventral segment. The other node must therefore occur at a distance of a half segment, or one-third of the length of the vibrating portion of the rod, below the free end, the

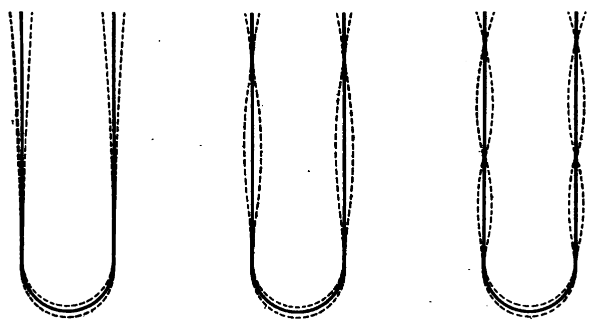
remainder of the rod forming a whole segment (Fig. 40). Likewise when the third partial arises, the rod forms two and one-half ventral segments, with the first node located at one-fifth of the length from the free end, while each of the entire segments occupies two of the remaining four-fifths (Fig. 41). Succeeding partials would continue to divide the rod according to the odd numbers, 7, 9, 11, &c.

Relations of these partials as to pitch.

These upper partials rise very rapidly in pitch, and are inharmonic in character. Thus the first upper partial has about 6¼ as many vibrations as the fundamental, while the next has 17½ as many. We can very readily hear the high overtones which ring out as we strike a tuning-fork, but which afterward vanish, leaving the fundamental.

Partials of tuning-forks.

A tuning-fork is subject in each of its branches practically to the same laws as are rods fixed at one end. When giving out its fundamental it vibrates with a node at the lower extremity of each branch, which corresponds to the fixed end of the rod. The three segments thus formed vibrate in unison with one another. Two other nodes



1 6¼ 17½

Fig. 42.

are formed upon the appearance of the second upper partial, and still two more with the third, these upper partials bearing

the same relations of $6\frac{1}{4}$ and $17\frac{1}{2}$ vibrations respectively to their fundamental as did the rods before discussed (see Fig. 42). It should be noted, however, that the vibration numbers vary somewhat in the case of forks of different shapes and materials.

Vibrations of rods free at both ends.

Rods with both ends free, employed in instruments like the *xylophone* and *metallophone,* were investigated with great care by Chladni (1756-1827), who has received the appellation of "father of modern acoustics." The primary motions of such a rod are seen by holding a six-foot flexible stick about a foot from each end. When the stick is shaken it oscillates between the positions shown in *A,* Fig. 43, the points at which it is held forming nodes. Held nearer the ends, it vibrates as under *B,* with three nodes. As its fundamental, which occurs when the two nodes alone are present, a free rod gives out a tone $6\frac{1}{4}$ times as acute as the fundamental of a similar rod fixed at one end, or a tone corresponding to the first upper partial of the latter. The succeeding partials rise rapidly in pitch, bearing about the same relations to their fundamental as those in connection with rods fixed at one end.

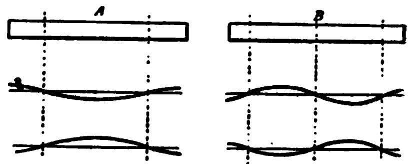


Fig. 43.

Partials produced when rods vibrate longitudinally.

Longitudinal vibrations may be produced in a rod by clamping it in the middle and rubbing one section lengthwise. If an ivory ball be suspended against one end of the rod, as in Fig. 44, it will be repelled vigorously. Savart, indeed, found that it was possible, by thus rubbing a glass tube with a wetted cloth, to shatter one end of it by

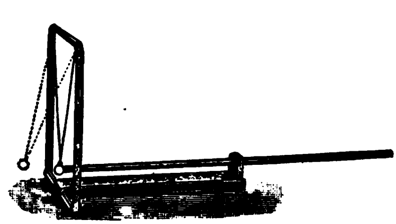


Fig. 44.

the force of its own molecular motion. Free rods vibrating longitudinally may be divided into 2, 3, 4, 5 segments, and so on, the vibrations of which form harmonic partials like those of strings. When these rods are fixed at one end, the tones which they develop are in the order of the uneven harmonic partials, 1, 3, 5 and so forth. A curious instrument devised by Marloye (1795-1874) is furnished with rods of wood or glass which are played upon by rubbing lengthwise with rosined fingers (Fig. 45).

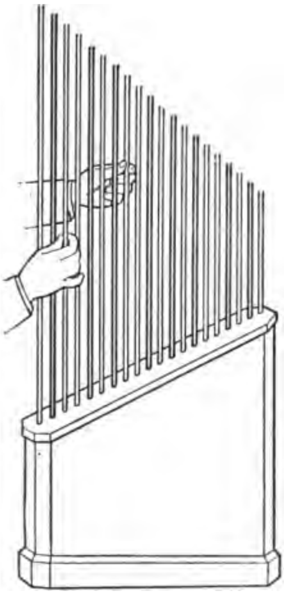


Fig. 45.

Chladni's experiments with plates.

Chladni conducted a series of interesting experiments while studying the motions of sounding glass or metal plates. Some of his results may be appreciated by employing a square plate fixed to a support in the middle. If fine sand be strewn upon this plate and the plate be made to sound by drawing a violin bow against one edge, as in Fig. 46, the sand will be violently agitated. Press a finger at the middle of one side and the sand will collect along the four intersecting nodes thus generated. In Fig. 47, which shows the result of this experiment, the plus and minus signs indicate that the alternate segments are vibrating in

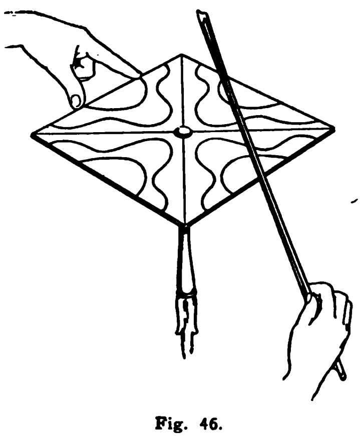


Fig. 46.

opposite phases: that is, that when one segment vibrates outward, the ones adjacent vibrate inward. In Fig. 48 the finger has been pressed against one corner of the plate, while in Fig. 49 two other points have also been touched. When the plate is divided as in Fig. 47 the fundamental is sounded. The division shown in Fig. 48 gives a tone a fifth higher; and

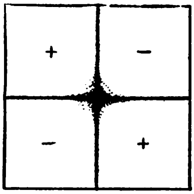


Fig. 47.

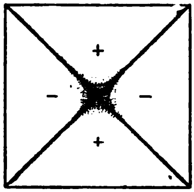


Fig. 48.

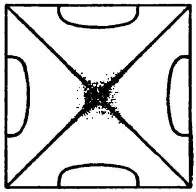


Fig. 49.

more complicated divisions result in tones still more acute in pitch. By touching the plate at various other points a multitude of beautiful figures may be evoked, such as those shown in Fig. 46.

Effect on light powder of vibration of plates.

When the plate is strewn with a very light material, such as lycopodium powder, the effect of the vibration upon this is exactly the opposite of what it was upon the sand, since the powder collects at the centre of the segments instead of along the nodes. The reason for this fact is that the exceedingly light particles are drawn into the vortices of the minute whirlwinds which are generated by the vibrating portions, and so are heaped up upon these latter.

Other plate figures.

Compound sand figures have been produced by placing one plate on top of another in such a way that vibrations of opposite phases were superimposed. Circular plates or disks also give rise to other interesting sand designs, which follow the same general laws as those governing square plates.

A bell may be regarded as simply another form of disk. Where the hammer strikes the side of a bell a ventral segment

Partials of bells.

is formed; and when the fundamental is sounded the bell divides into four of these segments, separated by nodes. Fig. 50 shows a glass bell against the edge of which, at equal distances, ivory balls are suspended. When these touch the nodes they remain nearly quiet; but when they are in contact with the segments they are forcibly repelled. These divisions are again shown on the surface of the water in the glass bell *A* pictured in Fig. 51, where the nodal lines *f e* and *g h* intersect the agitated parts of the surface and the maximum disturbance is at *a, b, c* and *d*.

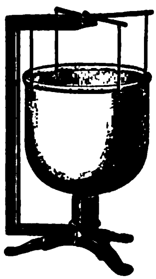


Fig. 50.

Fig. 51.

Peculiarities of bells.

Many inharmonious partials would be elicited from a bell of uniform curvature and thickness; and, to avoid these, various shapes and materials have been employed. Famous makers like Van der Gheyn (1550) and Hemony (1650) have formulated laws and patterns which are generally observed by bell founders. The fact that the segments of large bells are seldom in perfect unison with one another, owing to slight unevennesses in construction, causes the frequent presence of beats (page 47).

Partials of membranes.

Stretched membranes are practically plates of great tenuity and flexibility. While possessing similar properties of forming nodes and segments, their extreme sensitivity and power of producing almost any series of vibrations makes them valuable as agents of sound-transmission (page 82). Their musical uses are chiefly in connection with instruments of percussion.

Confined portions of the air or of gases may be made to emit sounds of great musical beauty. All the wind instruments

Tones of sonorous tubes.

of the orchestra, indeed, are offshoots of this phenomenon. The principles on which these instruments are based are the same as those which govern the tones of *sonorous tubes,* which we now proceed to consider.

Proof that the air in a tube vibrates.

That it is really the air within these tubes which vibrates and not the solid exterior walls can be easily shown by experimenting with three tubes of exactly the same size but of different materials, such as glass, copper, and cardboard. It will be found that the tones of all three are practically identical, and therefore independent of the composition of the tube itself.

A sound-wave in a stopped tube.

Taking now *a tube closed at one end* (Fig. 52), we set the enclosed air into vibration by blowing gently across the open top. Immediately a pulse of condensation passes from *a* through *b*, and *c*, and is reflected back at *d*. An accompanying pulse of rarefaction follows the same course, so that the tube is traversed lengthwise four times in the passage of a single sound-wave, or, in other words, each sound-wave is four times the length of the tube. By filling the tube with various gases, tones of different pitches are produced. Since, however, their sound-waves are all equal in length, the relative velocity of sound in the air and in these gases can be easily calculated.

Fig. 52.

Upper partials of stopped tubes.

At the end *d*, where there is the greatest alternate condensation and rarefaction, there is yet the least motion; hence a node is formed across the tube at this point. A maximum of movement must always take place, however, at the open end *a*, which is thus always the middle of a ventral segment. When the air in the tube vibrates under a more powerful current, the first upper partial is formed; and the additional node is a third of the length of the tube from its top, just as was the case with a rod fixed at one end. In like manner the succeeding partials are formed by divisions of the tube according to the odd numbers, 3, 5, 7, and so forth, as shown in Fig. 53. These partials,

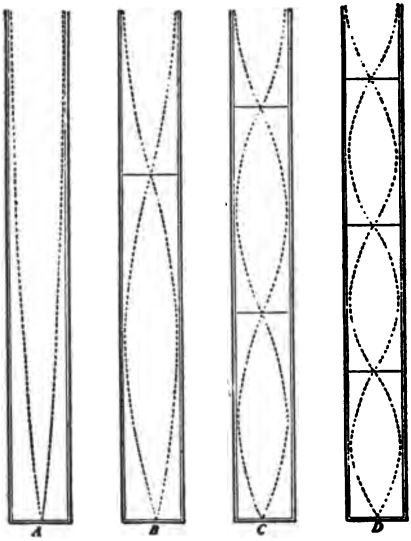


Fig. 53.

unlike those of rods fixed at one end, are members of the harmonic series of strings (Fig. 37).

Tubes open at both ends involve conditions somewhat different from those just discussed. A pulse of condensation entering such a tube (Fig. 54) at *a*, passes through *c* to *b*, where it rushes out into the free air, generating at the same time a pulse of rarefaction, which starts back from *b*. Another pulse of rarefaction, however, starts simultaneously upward from *a* at the same rate; and these **two pulses**, encountering each other at *c* with equal force, leave the air at *c* in a state of rest, or, in other words, form a node there, each of the pulses then rushing by to its destination at the end opposite to that from whence it came. Pulses of condensation now start back from each end, meeting at the nodal plane *c* as did the pulses of rarefaction.

A sound-wave in an open tube.

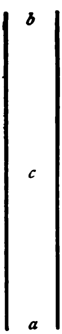


Fig. 54.

It is evident, therefore, that a complete sound-wave involves the passing of a pulse of condensation from *a* to *b* and a return of a pulse of rarefaction from *b* to *a*, or, in other words, a length of twice that of the tube itself. Inasmuch, however, as the length of a sound-wave in a stopped tube was four times the length of the tube, it follows that **an open tube must give a fundamental tone an octave higher than that of a stopped tube of the same length, since its sound-wave is only one-half as long.**

Length of a sound-wave in an open tube.

With the formation of upper partials in an open tube, both ends of the tube, where the points of maximum motion are located, will always be centres of ventral segments. When there are two nodes, forming the second partial, an entire segment will consequently arise in the middle of the tube, and a half segment at each end;

Partials of open tubes.

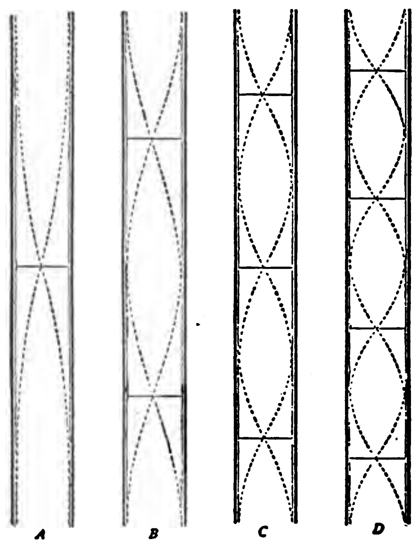


Fig. 55.

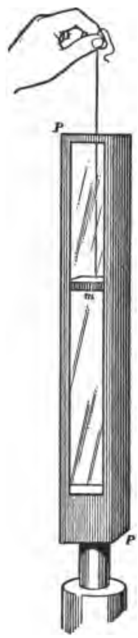


Fig. 56.

hence the nodes will be a quarter of the length of the tube from each of its ends. The tone thus given out is an octave above the fundamental. The third partial, sounding an octave and a fifth above the fundamental, has nodes one-sixth of the length from the ends and also a node in the middle; while the fourth partial, sounding two octaves above the fundamental, has nodes one-eighth of the length from each end, with two others at equal distances between. All these effects

are shown in Fig. 55. The upper partials in this case follow the harmonic series unbrokenly in the succession 2, 3, 4, 5 and so on.

Location of nodes and segments.

A clear method for showing the position of the nodes in tubes open at both ends is shown in Fig. 56, where such a tube is represented by an open organ pipe *P P*, having one of the sides made of glass. If this pipe be put into vibration and a small stretched membrane *m* strewn with sand be lowered into it, the sand will dance about where the motion is greatest, but will remain quiet when a node is reached.

Modifications of theoretical laws.

Tubes of which the length is great in proportion to their diameters follow quite closely the law suggested above, that **the pitch is inversely proportional to the length of the tube.** The pitch may be considerably affected, however, by greatly increasing the diameter. Various other conditions as to the shape of the tube cause modifications of its theoretical laws, and must be taken into consideration by instrument makers.

SUMMARY

The quality of a tone depends upon the number, position, relative intensity and phases of the secondary tones which are mingled in it. The relation of these upper partials, as they are called, to the fundamental may be expressed by simple whole numbers, in which case they are called harmonic partials, or by fractional numbers, when they are called inharmonic partials. Given complex tones can be reconstructed only in so far as they contain the simple harmonic partials.

In forming their partials vibrating bodies divide up into nodes and ventral segments. The presence of several partials causes complicated motions in the vibrating body. Strings form their partials in an harmonic series, the members of which are related to each other as the successive simple whole numbers. The partials of rods, plates and membranes are generally inharmonic and high-pitched. They are formed under various and sometimes complicated conditions.

Tubes, either stopped at one end or open at both ends, give out musical tones by the vibrations of the air or gases with which they are filled. While in both cases the harmonic series of partials is produced, in that of stopped tubes only the odd partials are possible, while the entire series can occur in tubes open at both ends.

REFERENCE LIST.

Helmholtz, Chapters 5, 6.
Tyndall, Chapters 3, 4, 5, 6.
Zahm, Chapters 4, 5, 6, 9.
Poynting and Thompson, Chapters 5, 6, 7, 8.
Barnes, Chapters 3, 6, 7, 8.
Harris, Chapters 8, 9, 10, 11.
Taylor, Chapter 4.
Broadhouse, Chapter 8.
Stone, Chapter 5.
Lavignác, Chapter 1, A.
Barton, Chapter 5.
Blaserna, Chapter 8.
Pole. Chapter 3.

CHAPTER VI

RESONANCE

NOT only do sounding bodies transmit their vibrations to the surrounding atmosphere, but they also have the power of setting up sympathetic vibrations in other bodies, whether these latter are in direct contact with them or not. From these conditions many interesting results follow which are grouped together under the title of the *phenomena of resonance.*

The phenomena of resonance.

To understand the nature of these phenomena, we must recall the familiar mechanical law of cumulative impulses. The working of this law may be illustrated by an old-fashioned swing, well-freighted with children. Another child stands behind the swing-seat, and when he gives it a slight push it sways gently away from him, immediately returning in his direction. A second push increases the momentum, which grows still greater as the pushes continue, until the children are flying through the air in long sweeping undulations, to their great delight. Each push, however, must be given exactly as the swing-seat reaches the point nearest the pusher in order to be effective, since otherwise its motion would be retarded or might even be entirely stopped.

The law of cumulative impulses illustrated.

For another illustration of this law, let a heavy weight such as a cannon ball be suspended from the ceiling by a string, and let a slender thread be attached to the weight. By gently pulling upon this thread at the proper intervals the weight may finally be made to oscillate back and forth over a considerable arc. A more remarkable form of this experiment is performed by simply blowing puffs of breath against the weight, which may thus be induced to assume a motion almost as great as before.

Further illustration of the law.

Similar results follow when a ship is tossed about in the

trough of the sea, gaining momentum from the continued impulses of even comparatively small waves. Soldiers, when marching across a bridge, are commanded to break step, since otherwise the results to the structure from the accumulated momentum might be disastrous.

Practical examples of the law.

We may approach the musical application of this law by a few experiments with ordinary pendulums. Let two of these which have the same vibration rate be suspended from a bar of wood. If one of them be now set in motion it will communicate its vibrations to the other through the common supporting bar, so that both will oscillate alike. Further than this, if two clocks whose pendulums vibrate *almost* exactly in the same time be set side by side on a table, the quicker of them will draw up the time of the other until they move in unison.

Transference of pendulum vibrations. (a) When the pendulums have the same vibration rates.

In the case of the swing above alluded to, if the child had given a push at the expiration of every two oscillations instead of each one, the momentum would have increased as before, but more slowly. With one push to each three oscillations the motion would have augmented still more slowly, and with one push to each four oscillations the increase would have been very slow indeed. So, if one of two pendulums attached to a common bar vibrates twice as slowly as the other it will set the latter in vibration by adding to its momentum at every second swing; but this effect will occur more gradually than was the case when the pendulum had the same vibration rate. A corresponding lessening of influence will take place if the first pendulum has a vibration rate one-third or one-fourth that of its companion pendulum.

(b) When the pendulums have different vibration rates.

Let us now hold in either hand one of two tuning-forks which have exactly the same vibration number. Striking one of these and soon after damping it with the fingers, we are able to hear a faint response coming from the other. If the

vibration numbers of the two forks were not the same, no such tone would be produced. When these are equal, however, **the fork originally sounding impinges its vibrations upon the other through the medium of the air,** just as the pushes were given to the swing, or the puffs of breath struck the suspended cannon ball. A pulse of condensation proceeding from the first fork hits the second, giving it a slight forward momentum. Its return is then facilitated by coincidence with the rarefaction which has followed the condensation from the first fork. Another pulse of condensation now strikes the second fork, and the whole process is repeated with slightly increased momentum. Thus the motion accumulates, as in the examples above cited, until the second fork sings steadily with the first.

Sympathetic vibrations of tuning forks.

But a tuning-fork may with equal facility incite sympathetic vibrations in bodies unlike itself. Let us hold our sounding fork over a glass jar, as in Fig. 57, first ascertaining the pitch of the air-column in the empty jar by blowing gently across its mouth. If this pitch is higher than that of the fork it will be necessary to lower it by "shading," which is accomplished by partly closing the mouth of the jar with a card or other flat object. If, however, the pitch of the jar is lower than that of the fork, water may be poured in until their vibration numbers coincide. The point at which they are in unison may be easily determined, since **the tone of the fork will become reinforced by the resonance of the air in the jar when the vibration numbers approach each other closely, and this resonance will attain a maximum when they are exactly the same.**

Effect of a tuning-fork upon an air-column.

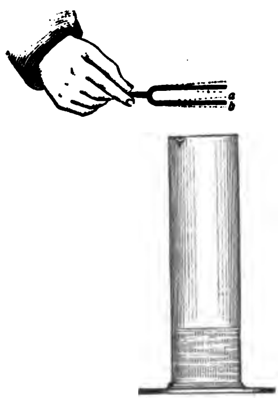


Fig. 57.

Under the latter condition what takes place is as follows:—When the prong of the fork moves to *b* (Fig. 57) a pulse of condensation runs down the jar as far as the water level, whence it rebounds; and when the prong moves to *a* a pulse of rarefaction performs the same process, the entire sound-wave thus equaling four times the distance from the mouth of the jar to the water level, as might be expected in the case of a tube stopped at one end (page 64). Knowing the vibration rate of the fork we may now calculate what should be the length of the air-column in the jar. If the fork gives 435 vibrations per second to *a'*, for instance, the length of its sound-wave must equal the velocity of sound per second, or 1120 feet, divided by 435, and the length of the air-column must consequently be about seven and one-half inches, which is one-fourth of the result of this division. In the case of a tube open at both ends the air-column is twice as long, or about fifteen inches. We may test the accuracy of these conclusions by rolling up a piece of cardboard so that it forms a tube fifteen inches long and an inch in diameter, and holding over one end the sounding fork, when the tone should swell out considerably. Extending or diminishing the length of this tube will reveal the condition of greatest resonance.

Explanation of this effect.

It was noted that the tone of the fork begins to be reinforced a little before the point of maximum resonance is reached. This result occurs from the fact that the flexible character of the air-column allows it to be more easily influenced than the more rigid tuning-fork, which required absolute unison with another sounding body before it could be affected by it.

The point of reinforcement of the tuning-fork.

Savart devised an apparatus shown in Fig. 58 which vividly illustrates the phenomena of resonance. A bell *T P* is mounted on a stand *D F C* to which is attached at *B* a resonating chamber *A*. In this chamber is a piston which provides for the regulation of its length. When the bell is sounded by a violin bow and the

Savart's resonating device.

piston is moved back and forth the varying degrees of resonance are perceived, the maximum sounding with great power.

Resonating chambers such as this are sometimes attached to

Fig. 58.

tuning-forks to heighten their effects. More often, however, the forks are mounted upon resonating boxes which are constructed of a size calculated to insure the best results, and which are left open at one or both ends. Thus a fork having a vibration rate of 384 requires a box open at one end only, having a length of 7.3 inches, a width of 3.8 inches and a depth of 1.8 inches. A fork thus mounted is shown in Fig. 59.

Resonating boxes.

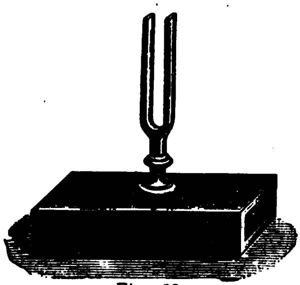


Fig. 59.

By experimenting with two reinforced forks of the same vibration rate some interesting results may be obtained. Placing them a short distance apart and pointing the open ends of their resonating boxes toward each other, let us sound one of the forks by a violin bow. Immediately the other responds with a strong tone, which continues after the first one is damped with the fingers. If we now release the first fork

Experiment with reinforced tuning-forks.

and afterward damp the second, the first will again sound, having taken its motion from the second; and this process of transference may be repeated until the energy of the vibrations is entirely exhausted. Again, if one of the forks be put slightly out of tune with the other by attaching a piece of sealing wax to one of its prongs, it will still respond, since the vibrations will be transmitted through the resonating boxes, although the response will be much feebler than at first.

While we originally placed the unison forks near together, such proximity is not necessary, since if we separate them by the length of the room they affect each other nearly as powerfully as before. Dr. Koenig made some interesting experiments on this line with two tuning-forks each having a vibration rate of 128 per second, through the conduit of Saint Michel, in Paris By pointing the open ends of their resonating boxes toward each other he was able, upon sounding one of them, to elicit a response from the other at a distance of over a mile.

Effect of distance upon resonance.

Whenever a body is free to vibrate in unison with a sounding body in its vicinity such sympathetic vibrations will be set up. If the two strings of the sonometer (Fig. 22) be tuned in unison and one of them be plucked, the other will respond. We have often felt the vibrations of an entire edifice when it acted in sympathy with a deep-toned organ pipe. A tone sounded on the piano may cause a chandelier or a window pane to jingle violently. The writer was once playing upon the piano when, from the force of a loud tone to which it responded, a large bowl of heavy glass in an adjoining room was shattered.

Conditions favorable to resonance.

Fig. 60 shows a device called a *sound-mill,* in which mechanical use is made of resonance. Four small cylinders each open at one end are attached to radiating arms balanced upon a central pivot so that they revolve freely. When the tone to which they are all

The sound-mill.

Fig. 60.

tuned is sounded the pressure upon the node at the bottom of each causes them to rotate as long as the sound continues. No motion will be produced unless the actuating tone be absolutely in unison with that to which the cylinders are tuned.

The resonators devised by Helmholtz have already been described (page 52). Each of these instruments has the power of selecting out one simple tone to which it responds. Other forms of resonators have also been invented which may be adjusted to more than one tone, or which may respond to several tones at once. Perhaps the most startling results, however, are produced by an instrument of this species which reinforces the murmuring sounds constantly flitting about in the atmosphere, but which are ordinarily imperceptible to the ear. In the form of a straight trumpet with apertures in the sides for changing its resonating pitch, this *melodiaphone*, as it is called (Fig. 61), when adjusted to the ear permits one to hear a succession of tones which are thus raised from insignificance into power. The singing of the seashell when it is held to the ear furnishes another illustration of the same principle.

Various forms of resonators.

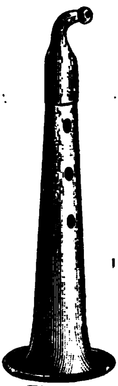


Fig. 61.

In the case of wind instruments, which are really tubes of various sizes and shapes either stopped at one end or open at both ends, the air-columns are set into vibration in one of two ways, the first of which is by directing a stream of air toward a sharp edge at the mouth of the tube, and the second by causing a reed annexed to the air chamber to vibrate. Examples of the former method are found in flutes and the flue pipes of the organ, while the latter is exemplified in clarinets, oboes and the reed pipes of the organ.

Resonance of wind instruments.

The exact manner in which vibrations are incited in pipes of the flue or "whistle" type is still a subject of controversy.

How flue pipes are made to speak.

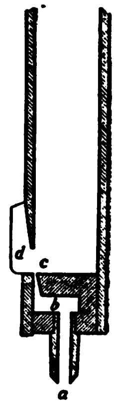


Fig. 62.

Fig. 62 represents a section of an organ pipe of this kind. In this the air, forced from the wind chest through the tube *a*, enters the chamber *b*, whence it rushes in a thin sheet through the small aperture *c* toward the sharp edge at *d*. Helmholtz asserted that the hissing noise made at this point is caused by a mixture of tones to one of which the pipe responds by resonance. A later theory which has met with much approval is that the thin layer of air directed across the embrochure *d e* acts like a reed and so invigorates the air in the large chamber of the pipe. The general and sectional view of a wooden organ pipe in Fig. 63 and of a metal one in Fig. 64

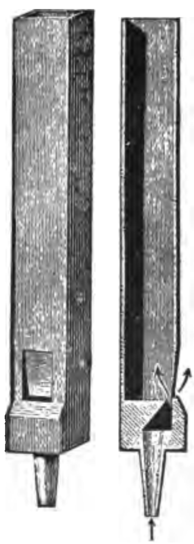


Fig. 63.

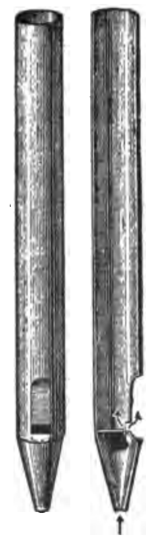


Fig. 64.

shows the structure of these and the position of the air-inlets.

A reed properly consists of a thin, narrow strip of flexible

Construction of reeds.

material, fixed at one end. Organ reeds, commonly of metal, vibrate over a rectangular orifice either slightly narrower and shorter than the free part of the reed itself or just large enough to permit the reed to move within it. In the former case the vibrating reed hits the sides of the orifice and is called a *striking* reed, while in the latter case it is called a *free* reed. The top and side views of a free reed are given in Fig. 65. The tongue z z is attached to the metal block a a, vibrating between the positions at z_1, and z_2, B. The air, passing in the direction of the arrows, is emitted in a series of puffs similar to those of the siren. Since the resulting tone is very rich in upper partials, some of which produce a strident effect, it is necessary for musical purposes that one of the tones, most often the fundamental, should be so reinforced as to overcome the presence of these discordant elements: hence the reed is generally used in connection with some form of a resonating tube. The fact should be especially noted that **the tone of the reed is caused by the puffs of air to which it gives rise, and not by the vibrations of the tongue itself.**

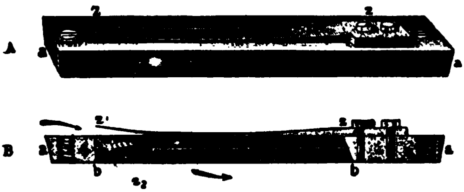


Fig. 65.

Use of reeds in organ pipes.

Examples of the use of both free and striking reeds in organ pipes are pictured in Fig. 66, A illustrating the former and B the latter. A conical tube such as is shown at the top of the pipe A is frequently superimposed, in various shapes, to modify the quality of the tone. For changing the pitch of the reed a tuning wire, which presses against it, may shorten the vibrating part, thus raising the pitch, or may lengthen it, with the opposite result. In B the air rises into the large chamber through the tube at the lower end. Passing into the semi-cylindrical tube r r, which is fastened to the block s s, it sets into vibration the

reed *i*, which causes the air in the chamber to sound by sympathetic vibration. For this latter result to occur it is necessary that the air-column in the chamber should be at least nearly of the same pitch as the reed itself. Since the reed is of metal and therefore of considerable rigidity, it forces the air-column to assume its own vibration rate, unless the rates of the two bodies are too much at variance. In instruments in which the reeds are composed of very flexible materials the air-columns impose their pitches upon the reeds.

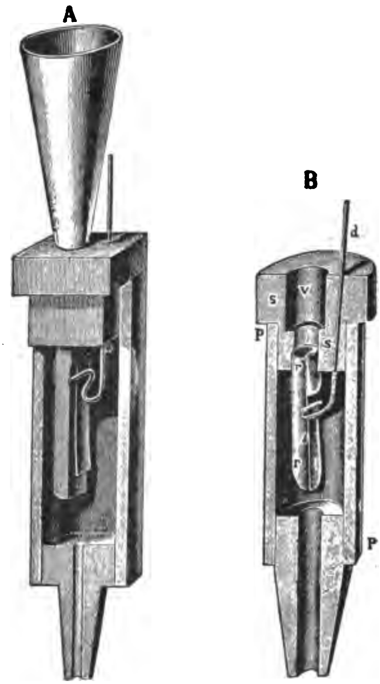


Fig. 66.

What has thus been said about organ pipes may be applied with various modifications to all kinds of wind instruments, consideration of the individual peculiarities of which is reserved for a special chapter. The nature of reed action in relation to the voice is of particular importance.

Resonance in other instruments.

Air-columns may also be set in vibration by gas-flames. Common illuminating gas may be used for this purpose, but better results follow from the employment of hydrogen. In Fig. 67 hydrogen gas, generated in the bottle on the left, passes into the tube in the rear and is ignited as it emerges from a small opening in the top. When a glass tube of the proper dimensions is placed over the flame thus produced a clear, musical tone is heard.

Singing flames.


Fig. 67.

Faraday (1791-1867) demonstrated that the gas-flame when sounding emits a series of explosions equal in number to the vibration rate of the air-column in the tube, which consequently resounds to these impulses. Beside their fundamentals, such tubes may give out several upper partials when excited by the flame. A much stronger fundamental tone and a greater number of upper partials may be obtained from large copper tubes under the influence of singing flames. Kastner (1852-1882) constructed a kind of pipe organ in which, when a key was depressed, two small flames were brought together in a pipe so that a tone was produced. The device, however, proved more curious than of practical value.

Sensitive flames.

Tyndall and several others investigated the phenomena of sensitive flames. A common "bat-wing" burner when under ordinary pressure assumes the form at the left of Fig. 68, and is unaffected by sounds. When

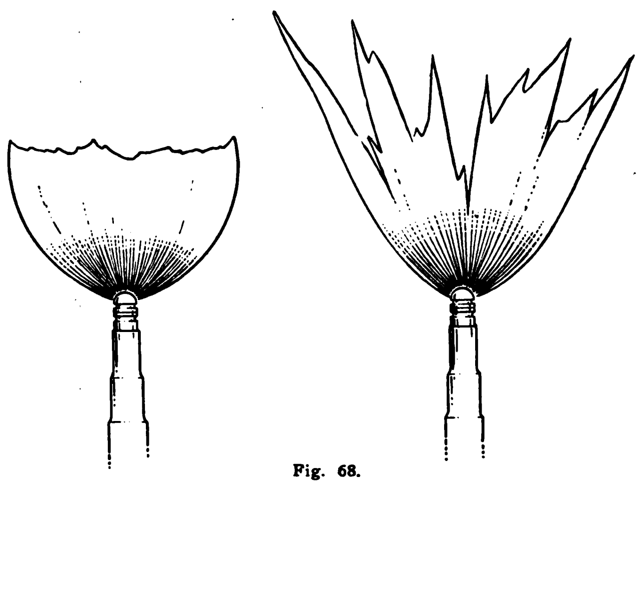


Fig. 68.

the gas pressure is pushed beyond a certain point the flame "flares" in the manner depicted in the right-hand drawing. If now the gas be regulated so that the flame is just on the point of flaring, the latter becomes sensitive to certain sounds, and darts out into a forked appearance whenever these are produced. This flaring normally arises from a certain amount of friction generated by the rush of gas from the burner; and when the force of the gas has nearly reached this point the agitation of the flame produced by its vibrations in sympathy with a sound is sufficient to cause it to lose its equilibrium.

By experimenting with different burners scientists have succeeded in producing flames of a high degree of sensitivity.

The steatite burner.

What is called a *steatite* burner gives, under normal conditions, a delicate flame about twenty inches long, of the form on the left in Fig. 69.. Influenced by different sounds this flame assumes various other sizes and shapes, such as the one on the right in Fig. 69. High upper partials, like those present in the vowels *i* or *e*, cause special agitation. When separated from its burner by a wire gauze the flame becomes so sensitive that it responds even to sounds inaudible to the ear.

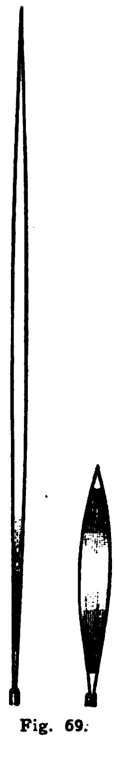


Fig. 69.

Effect of sound on unignited gas.

That it is not the flame itself which is thus sensitive to sounds but the gas as it escapes from the burner, has been proved by substituting for the flame unignited gas charged with smoke. Shapes similar to those assumed by the flame are formed by such gases when responding to a musical tone.

Effect of resonance on bodies of multiple vibration rates.

As might be expected from the experiments with pendulums of unequal length recorded on page 70, a tone is able to influence not only bodies vibrating to the same pitch but also those having

the relation of the simple harmonic upper partials to the sounding body. Thus a tuning-fork may induce resonance in a jar whose vibration rate is twice, thrice, or four times its own. If a tone be sung when the dampers are lifted from the strings of a piano, not only will the string which gives the same note resound, but also a number of tones representing higher partials will be clearly heard. Press down the keys representing the chord *c' e' g'*  on the piano and strike *c*  sharply, releasing it immediately afterward. The group of upper strings will be set into vibration induced partly by the fundamental of *c* and partly by its upper partials.

Likewise **tones coincident with the upper partials of another tone may cause these to sound.** Holding down *c*  on the piano, play and release a number of the upper *C*'s, *E*'s and *G*'s. Many of these will now be heard vibrating as partials of the original *c*. To prove this fact let go of the key which is being held down, when by the consequent fall of its damper the sounds will immediately cease.

Upper partials induced by resonance.

Certain substances have so complicated a structure that they are apparently capable of reinforcing any sound whatever. One of these is wood. Place the end of a sounding tuning-fork against the top of a wooden table, and a great increase in its tone will result, whatever be its rate of vibration. So also the tones of a music box, when the latter is brought into contact with a wooden surface, are much reinforced. In the case of the resonating box above alluded to (page 73) the tone of the tuning-fork is intensified not only by the air-column in the box but also by the wood of which the latter is made.

Wood as a resonator.

Without reinforcement the tone of a string is so slight

as to be scarcely perceptible. This fact can be proved by stretching a string, suspended in free air, by means of an attached weight. When the string is vibrated by a violin bow little or no sound is heard; but if it be subjected to an equal tension when stretched over a board a tone of considerable volume results when the string is sounded. Thus the full and rich tones proceeding from a piano come in reality from the vibrations of the sounding-board which have been set in motion through sympathy with the vibrating strings.

Sounding-boards.

Experiments with sounding-boards.

We may realize the agitation of the sounding-board in the piano by placing a small object such as a pencil upon it. When a tone is produced to which it can respond, the pencil will jar disagreeably, impelled by the board with which it is in contact. A familiar children's toy was at one time made in the form of small figures or "puppets" which when set upon the sounding-board waltzed about merrily, and which could easily be overthrown by an especially heavy tone.

Resonance in stringed instruments.

All forms of stringed instruments require such reinforcement. Those of the violin type reinforce the string tone both by their wooden bodies and also by the air enclosed within them. In the case of the banjo, the sounding-board is replaced by a stretched membrane like a drum-head which also is capable of resonating to any tone, producing, however, a resulting sound of a duller, less elastic quality.

Uses of membranes.

Membranes, on account of their extreme sensitivity to all sounds, have been made the bases of important appliances for recording and reproducing sound. An instance of such use is found in the drumskin of the ear, which conveys exterior sounds to the organs within (page 109). In the *phonograph* and the *telephone,* membranes have a similar function to perform.

The principle upon which the phonograph works was known for some time before the invention of the present instrument,

and was employed in an experimental device called the *phonautograph*. The latter consisted of a large funnel which focused sounds directed into it upon a membrane at the end. To this membrane was attached a style which recorded the vibrations in zigzag lines upon smoked paper covering a revolving cylinder. **The phon-autograph.**

Most of these features were retained in the *phonograph* invented by Edison in 1877, but in the latter instrument the style made indentations in a piece of tinfoil at varying depths, so that, when the style was placed back at the beginning of these indentations and caused to retrace them at the same rate as at first, both the style and the membrane approximately repeated their former motions, and hence gave out sounds similar to the original ones. **The phonograph.**

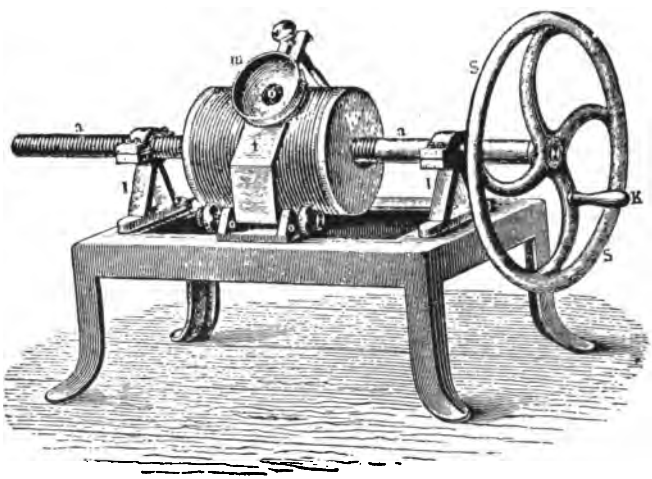


Fig. 70. Original of the Phonograph.

The nature of this historic instrument may be better understood by consulting Figures 70 and 71, which give a general and sectional view of its original form. Sounds travel down the funnel *P P* through the mouthpiece proper *m m* focusing

on the membrane or diaphragm *n n* fixed in the bar *t* which is pivoted at *o* and adjusted by the screw *c* at the top. Attached to the diaphragm is a small plate, which carries

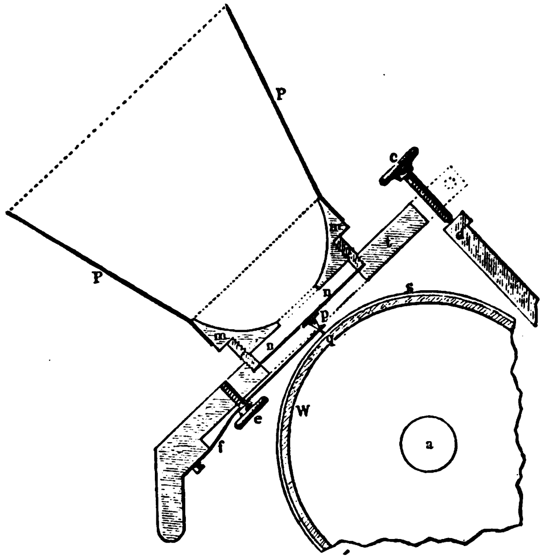


Fig. 71.

the style *p*. This style is not directly in contact with the tinfoil but presses on a spring bearing a small rounded metal point *q* which indents the tinfoil *s* on the revolving cylinder *W*. As this original machine was worked by hand, difficulty was experienced in producing absolute regularity in the motions, a defect which is remedied in the modern machines by the use of a mechanical motor. Various forms of the phonograph are now on the market, in which the records are made in a wax composition from which they are afterwards reproduced in firmer materials. Some machines still employ the cylinder form of records, while in others, sometimes termed *gramophones*, the vibrations are recorded upon a revolving horizontal

disk in spiral curves which proceed from the outer edge toward the centre.

The implement now used for cutting the record is different from that which reproduces it, the former consisting of a sapphire point and the latter of a similar point or a needle of metal or fibre. One of the greatest marvels of science is illustrated in the combined work of these little tools, the first of which ploughs into the wax a reproduction of not only a single sound with its attendant overtones, but frequently of many other accompanying sounds, each with its characteristic quality, and the second of which travels over each minute indentation with fidelity, transmitting its complex motion to the diaphragm, whence it is conveyed through the air to the ear of the listener. If we could trace out one of the grooves in this record with a microscope, its appearance would be found to resemble that presented by the ruffled surface of a lake seen through a slit in a card. Long indentations made by the fundamental tones would be seen traversed by numberless ripples, each corresponding to an overtone or another fundamental, and each having a depth proportional to its intensity.

How the tone is reproduced.

Several instruments have been devised to bring phonograph indentations into readable form. Professor McKendrick, of Glasgow, constructed a "phonograph recorder" from the results of which he was able to estimate the enormous number of vibrations involved in even quite simple sounds. In the record of the words *The Royal Society of Edinburgh*, for instance, he discovered over 3000

Experiments with phonographs.

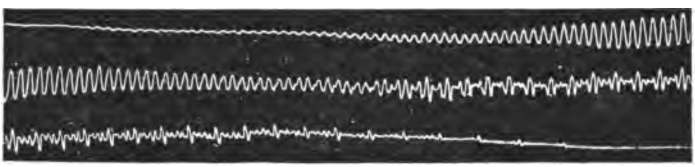


Fig. 72. Curve of the pronoun *I*.

vibrations. Fig. 72 shows a graphic record of the sound of the vowel *I*, made by Edward S. Wheeler, of Yale University, as the result of similar experiments. The possibilities of such devices in determining the composition of tones can readily be recognized.

The telephone.

The *telephone* also depends for its action upon the vibrations of a membrane which catches the sounds impinging upon it. In the *transmitter* these vibrations produce fluctuations in an electric current which carries them through a wire circuit to any desired place. There they in turn affect the membrane of the *receiver*, which reproduces them to the ear of the listener. Invented by Graham Bell in 1876, the telephone was at first of no commercial value on account of the indistinctness of the reproductions. By means of many clever devices which have enormously increased its sensitivity, however, it has now attained the position of a household necessity. At first no distinction was made between the transmitter and the receiver. While the latter has retained much of its original form, the transmitter is now quite different, its efficacy having been greatly augmented by the use of carbon. Animal membranes have been generally replaced in both phonograph and telephone by thin disks of mica or metal.

Resonance in the voice.

Perhaps the most remarkable manifestations of the phenomena of resonance, however, are found in connection with the human voice. By directing the air current into the cavities of the head, mouth and throat, and by modifying the shape of these cavities, the speaker or singer is able to produce an infinite number of modifications in tonal intensity and quality. Further consideration of this important phase of resonance is reserved for Chapter VIII.

SUMMARY.

RESONANCE, or sympathetic vibration, depends upon the principle that a number of slight impulses properly applied will finally create considerable momentum.

A very rigid body, to be affected by the sound coming from another body, must be either in perfect unison with this sound or must have a vibration rate which is a simple multiple of that of the sounding body. Bodies of less rigidity may respond when they are not absolutely in unison with the sound which strikes them.

Instruments called resonators are capable of selecting out special sounds for reinforcement, and may even develop sounds ordinarily imperceptible to the ear.

Air-columns in tubes can be made to resound under the influence of tuning-forks, the "whistle" device, reeds, and gas-flames.

Reeds in organ pipes are either striking or free.

Sensitive flames are of value for testing the properties of sounds.

Sounding-boards and membranes are apparently capable of responding to any sound whatever. The former are useful in reinforcing the tones of strings, especially those of the piano and of the violin family. Membranes are chiefly employed for recording and reproducing sound.

REFERENCE LIST.

Helmholtz, Chapter 3.
Barton, Chapter 6.
Zahm, Chapters 6, 7.
Tyndall, Chapters 3, 5, 6.
Harris, Chapters 7, 10.
Broadhouse, Chapters 6, 10.
Poynting and Thompson, Chapters 4, 7, 8, 9.
Stone, Chapter 3.
Taylor, Chapter 3.
Barnes, Chapters 4, 7, 8.

Lavignac, Chapter 1.
Catchpool, Chapter 5.
Blaserna, Chapter 3.

CHAPTER VII.

Scales, Intervals and Chords.

Having reviewed the chief facts pertaining to the nature and properties of sound, we will now inquire how certain sounds have been selected and systematized from the well-nigh limitless number at our disposal. In all probability, attempts at music in the form of vocal utterance were coëval with speech itself; indeed, many scholars contend that song antedated the spoken word. Certainly at a very early period in the history of primitive peoples mere insensate howlings must have given place to sounds of a more stable nature. When tones of varying pitches thus came to be employed in melodic progressions, they naturally ranged themselves in a graded series, each member of which was fixed in its relation to the others. Variety was also insured in this series or *scale* (Latin *scala,* a ladder) by the presence of intervals of different dimensions.

Origin of scales.

In using the word *interval* in music we should bear in mind that in defining it as *the difference in pitch between two tones* we refer not to the numerical difference between their vibration numbers, but to the *proportion existing between these numbers,* which remains constant for any given interval. Thus the upper tone of an octave, vibrating twice as fast as the lower, is related to it as two is to one; a proportion represented by the fraction $^2/_1$. If the lower tone vibrates 100 times per second, the upper must vibrate $^2/_1$ x 100 or 200 times per second, so that the difference between the vibration numbers will be 100; but if the lower tone vibrates 200 times per second the upper must vibrate $^2/_1$ x 200, or 400 times, with a consequent rate difference of 200. In both cases, of course, the interval is the same.

Definition of the word "interval."

Such a selection of tones as has been described is in many

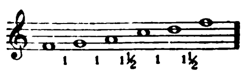
respects a purely arbitrary one, resulting in the formation of diverse scales among distinct nationalities. Nevertheless there are a few intervals which are common to nearly all musical systems. When, for instance, men and women attempt to sing the same tune, it is natural for them to pitch their voices an octave apart; and so intimate is the relation between these octave tones that the participants often believe that they are singing in unison. For the same reason we speak of a tone as *repeated* in another octave when the two tones are an octave or a multiple of an octave apart. Hence the characteristics of any scale are always included within the compass of an octave, while any extensions of the scale will arise from the repetition of the same intervals in succeeding octaves.

Common use of the octave.

The *whole tone* or *whole step,* approximately one-sixth of an octave, is the general unit of measurement. Other intervals frequently found are the perfect fifth and perfect fourth, represented in our scale by *C-G* and *C-F,* and measuring respectively 3½ and 2½ steps. Except in the case of the intervals cited, however, there is little uniformity in different systēms.

Other intervals in frequent use.

We may in general distinguish two classes of scales, the first of which avoids intervals smaller than a whole step, while the other subdivides the step into intervals which are sometimes exceedingly minute. The chief scale of the first class is the *pentatonic* or *five-note* scale, which embraces three whole-step intervals and two intervals of a step and a half each, thus:



(Figures beneath refer to steps and fractions of steps.) Its effect may be judged by playing in succession the black keys of the pianoforte. Chinese folk tunes are almost invariably founded upon this scale, which is revered as the supernaturally-sent foundation of music; and although in China twelve divisions of the octave are recognized in theory, the pentatonic scale still retains its prestige in practical usage.

Two classes of scales.

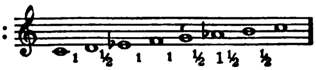
The pentatonic scale.

Japan and other Oriental nations employ a similar scale, while its existence in Scotland is plainly evidenced in popular melodies.

In our own system the octave is divided by semitones or half steps into twelve parts; and from a combination of five whole steps and two half steps the major eight-tone di-

Use of the half step.

atonic scale 

is formed, which is the basis of our music. Our harmonic minor scale employs the interval of 1½ steps between the sixth and seventh degrees, thus: 

In some scales still greater variety is secured by again inserting this interval between successive degrees of the eight-tone scale.

Scales with minute intervals.

Among strongly imaginative peoples there is a tendency toward the use of minute intervals. The ancient Hindoos, for instance, divided the octave into twenty-two parts, and the Arabs into seventeen, the latter determined in accordance with mathematical principles. A multiplicity of scales is the general sequence to so complicated a system of subdivision.

The foundation of the Greek scales.

Intervals as small as the quarter-step also existed in the scales of the ancient Greeks. Four tones arranged within the compass of a perfect fourth, seems to have constituted the earliest Greek scale. This received the name of *tetrachord,* or scale of four strings, from the fact that its tones corresponded to the tuning of the four strings of the original lyre. Terpander the Spartan, in the seventh century B. C., combined two tetrachords by a common note, producing a scale which had the compass of a seventh; and Pythagoras (died about 500 B. C.) increased this to an octave by placing a step between the two tetrachords.

The latter philosopher investigated the vibrations of strings

Theory of Pythagoras.

by means of the ***monochord,*** a primitive form of the sonometer (Fig. 22). In this way he discovered that when the length of a stretched string was divided in the proportion of two to one, the interval produced by sounding the two segments together was an octave; that a division of three to one resulted in a perfect fifth; and that one of four to three gave a perfect fourth. From these results he deduced the principle that "**the simpler the ratio of the two parts into which the vibrating string is divided, the more perfect is the consonance of the two sounds,**" a theory of which Helmholtz was the first to give a logical explanation.

The Pythagorean scale.

Pythagoras constructed an eight-note scale by starting with an octave and inserting the intervening tones found by proceeding by perfect fifths from the lower tone; thus beginning with the octave *C-C* he went from the lower *C* by fifths to *G, D, A, E* and *B,* lowering the tones outside the original octave to their position within it by octaves, and adding *F,* a perfect fourth above *C.*

Results of this scale.

Two results of this process should be noted. It was discovered that the third tone *E* was related to *C* in the complicated ratio of $\frac{81}{64}$, and hence the major third was classed as a discord. Then also Pythagoras found that if he extended his circle of fifths as follows:

C, G, D, A, E, B, F♯, C♯, G♯, D♯, A♯, E♯, B♯,

the final *B♯* was sharper by about $\frac{1}{78}$ than the nearest *C,* obtained by raising the original *C* by octaves, and that when he proceeded downward by fifths as follows:

C, F, Bb, Eb, Ab, Db, Gb, Cb, Fb, Bbb, Ebb, Abb, Dbb,

the final *Dbb* was flatter than its nearest *C* by the same amount. This discrepancy has been called the *Pythagorean comma.*

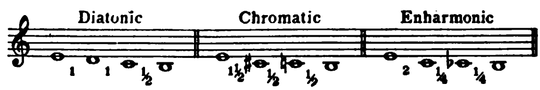
Greek modes.

With the tetrachord as basis the Greeks formulated three classes of scales or ***modes.*** The first or *diatonic* genus embraced all possible arrangements of whole and half steps within the compass of a fourth; the

second or *chromatic* genus combined two half steps with the interval of a step and a half; while the third or *enharmonic* genus embraced two quarter steps and an interval of two whole steps.

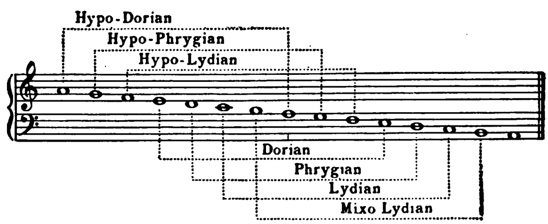
The following illustrations of Greek modes in modern notation do not represent their absolute pitches, which varied somewhat. Scales were conceived by the Greeks, in common with most early peoples, as proceeding downwards instead of upwards as in our musical system.

Examples of the three genera:



Diatonic genus and complete system.

Most important of these genera was the diatonic, of which seven modes were recognized. In each of these the octave compass was completed by joining two tetrachords together; and all became finally incorporated into a so-called "complete system," two octaves in length, to each note of which a name was given, taken from the nomenclature of the lyre strings. The result was as follows:



The complete Greek system.

Gregorian modes.

Undoubtedly Greek music played an important part in forming the music of the early Christian church. The latter, at first purely vocal, consisted of unison melodies, generally not more than an octave in compass and based upon scales that were not definitely formulated for some

time. Ultimately, however, these scales were arranged in a series of "church" or "Gregorian modes" supposedly the same as those of the Greek diatonic genus. Four *authentic* modes were supplemented by an equal number of *plagal* modes, each of which was a fourth lower than its corresponding authentic. Later on four others were added. Each mode had two notes of special importance, the final or ending note and the dominant or reciting note, which are shown in the table of the original modes formulated in Fig. 73.

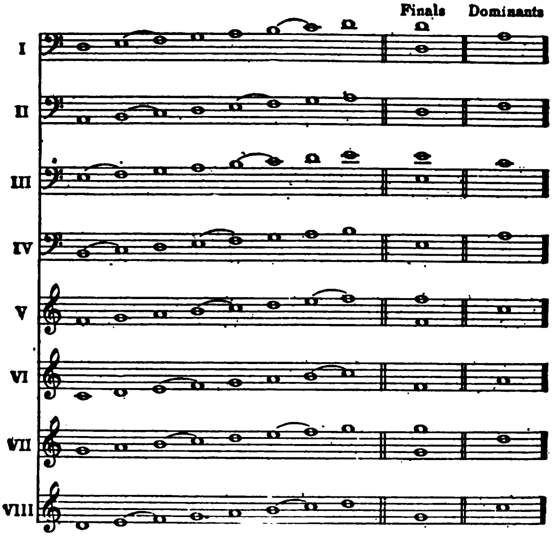


Fig. 73.

The numbers before the scales indicate the following modes:

Authentic.	*Plagal.*
I. Dorian.	II. Hypo-Dorian.
III. Phrygian.	IV. Hypo-Phrygian.
V. Lydian.	VI. Hypo-Lydian.
VII. Mixo-Lydian.	VIII. Hypo-Mixo-Lydian.

Half steps are shown by slurs, otherwise whole steps prevail. By the eleventh century all these scales were united in a long

scale of about two and a half octaves, extending from G to c'', and divided into seven overlapping scales of six notes each, called *hexachords.*

Rise of major and minor scales.

Meanwhile the dance rhythms and secular songs of the people were conforming to scales which were able to give a desirable sense of finality to the verse endings of rhymed stanzas of poetry. A tune and its accompanying harmonies were made to revolve around a *central tone,* to which an ending formula or *cadence* finally led. Thus *tonality* was evolved; and with it came the dominance of the so-called *major and minor scales* which eventually superseded the older forms.

Resulting problems.

This change in attitude, together with the growing complexity of music due to the popularity of instruments and the consequent rise of new forms, presented problems to the theorists of the later fifteenth and the sixteenth centuries which provoked much controversy. Let us see what these problems were, and how they were disposed of.

Location of diatonic tones.

It was first necessary to establish the proportion of the intervals of the major diatonic scale of eight notes, which came to be regarded as the basis of our musical system. This proportion was determined by adopting the relations discovered in the first fifteen harmonic partials resulting from the equal subdivisions of a vibrating string, as shown in Fig. 74. From this series we perceive

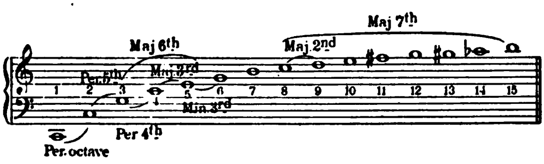


Fig. 74.

that the interval of a whole step, first required for constructing the scale, occurs between c'' and d'', the eighth and ninth partials. According to the laws of strings c'' must vibrate

eight times while d'' vibrates nine times; or, in other words, their ratio of vibration is 9 to 8, represented by the fraction $\frac{9}{8}$. This interval of a whole step is called a major second. Between c' and e' is the interval of two whole tones, called a major third; and for reasons similar to those just advanced the ratio may be represented by the fraction $\frac{5}{4}$. From g to c', a perfect fourth, we derive the fraction $\frac{4}{3}$; from g to e', a major sixth, the fraction $\frac{5}{4}$, and from c'' to b'', a major seventh, the fraction $\frac{15}{8}$. These results are summed up in Fig. 75, each fraction showing the relation which the note above it bears to the tonic c.

Fig. 75.

Other important intervals involved in this scale and also derived from the partials of strings are the minor third from e' to g', with the ratio of $\frac{6}{5}$, and the minor sixth, from e' to c'', with the ratio $\frac{8}{5}$.

The minor third and sixth.

The scale thus formed is called the "true" or "just" scale, in distinction from the "tempered" scale (page 103). We note that the major third is simplified to $\frac{5}{4}$ or $\frac{80}{64}$, against the Pythagorean major third of $\frac{81}{64}$, so that the upper tone of the latter is slightly sharper in pitch than that of the "true" third.

The "just" scale.

From the table, Fig. 74, we can also determine the ratio between contiguous scale notes by applying the mathematical principle that **the ratio of the difference between two intervals is found by dividing the ratio of the greater by that of the less.** The results are as follows:

Ratios between contiguous scale-tones.

$$C, \ \tfrac{9}{8} \ D, \ \tfrac{10}{9} \ E, \ \tfrac{16}{15} \ F, \ \tfrac{9}{8} \ G, \ \tfrac{10}{9} \ A, \ \tfrac{9}{8} \ B, \ \tfrac{16}{15} \ C.$$

We notice that, while the half steps have the same ratio of

$\frac{16}{15}$, the whole steps vary in size, three having the ratio $\frac{9}{8}$ and two the ratio $\frac{10}{9}$. The slight difference of $\frac{81}{80}$ between them is called a *comma.*

Origin of chromatic tones.

After the diatonic scale was thus formed the whole steps were subdivided by chromatic or "colored" tones, so-called because they gave varied shadings to a melody. These, at first used only by singers to give smoother voice progressions, were afterward adopted by composers, who discovered that they were available not only for melodic purposes but also as a means of changing the tonality, or *modulating.*

Location of chromatic tones.

To make this key-interchange possible the new tones must have the proper relations to the other tones of the scale in which they occur. Thus, since the seventh tone *B* of the scale of *C* is a major third above the fifth tone *G,* the same relation must exist between the fifth and seventh tones of the next scale, *G;* hence *F*♯ is placed a major third above *D.* In like manner *C*♯ is placed a major third above *A, G*♯ above *E, D*♯ above *B,* and *A*♯ above *F*♯. After locating the flats by a similar process we shall find that corresponding sharp and flat tones such as *F*♯ and *G*♭ are not exactly in unison, but that of the two the flat is a comma higher in pitch.

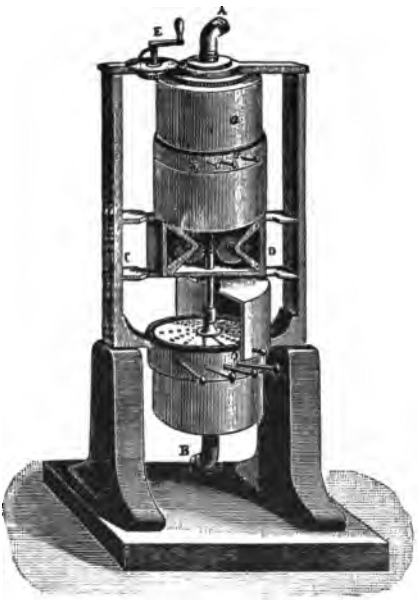


Fig. 76.

We have said that Helmholtz was the first

Helmholtz's siren.

to answer satisfactorily the question of what causes consonance and dissonance. For investigating the relations between the tones he invented the *double siren* (Fig. 76), which is a complex form of the instrument shown in Fig. 19. Helmholtz's siren contains two disks which can be rotated either individually or in unison. In the lower of these four sets of holes number 8, 10, 12, and 18 respectively, while four corresponding sets in the upper number 9, 12, 15, and 16. *A* and *B* are ducts through which the wind is introduced by pressure from an acoustic bellows. Keys at *a* and *b* serve to throw into action any desired series of holes. At *CD* is a clock-work device used to record the number of revolutions of the disks. Each of the latter is enclosed in a brass box which forms a resonator for certain tones. In the illustration a part of the lower box has been removed in order to reveal the disk. A crank attachment at *E* serves to raise or lower the pitch of the tone given by the upper disk, by rotating in either direction the cylinder which encloses it.

By employing the proper combinations of holes and rotating the disks in unison Helmholtz was able to produce the

Experiments with this siren.

different vibration ratios involved in the various intervals of the scale: thus by opening the series of sixteen holes in the upper disk and eight in the lower the resulting ratio of $\frac{2}{1}$ gives the octave, while the two series of eighteen and twelve holes, having the ratio of $\frac{3}{2}$ give the perfect fifth, and so on. The most significant result of these experiments, however, was in connection with the sound-interferences which cause *beats* (page 44). In the case of the octave and fifth no beats were heard, but with all the other intervals beats were present, varying in rapidity and intensity with the character of the interval. Generally, when any "true" interval was put out of tune by altering the pitch of the upper tone an acceleration of the beats followed.

Consonance and dissonance, according to Helmholtz, are determined by the nature and frequency of these beats. As to

Consonance and dissonance dependent on beats. the first of these factors, he showed that beats are produced not only by the fundamentals of two tones but also by their upper partials and even their resultant tones (page 47). Only the most prominent of these secondary factors are, however, strong enough to produce beats of any importance; and as their conflicts vary greatly in character there are wide differences in the relative intensities of their beats.

Frequency of beats. The effect of beats is determined even more largely by their frequencies. Very slow beats are not necessarily disagreeable, but as they grow quicker they affect the ear much as a flickering light affects the eye. After reaching a maximum of unpleasantness, however, they become merged together like the spokes of a revolving wagon wheel. Helmholtz concluded that when the number of beats given out by an interval lay within the disagreeable zone the interval was dissonant, and that if these beats either increased or decreased in number sufficiently the interval became consonant.

Effect of beats in different registers. Because, however, of the proportional nature of intervals, we might suppose that a much wider interval in the lower part of the scale would be dissonant than in the upper part, since the difference in actual vibration numbers of the upper intervals is so much greater. This condition does in fact result only to a limited extent since, as has been proved, the number of perceptible beats is smaller in the lower part of the scale than in the upper, although not in proportion to the increased number of vibrations which compose a given interval. If we play major or minor thirds on the extreme bass part of the piano and then in the treble register we are at once aware of the comparative roughness of the former.

Diagram of consonance and dissonance. To show graphically the degrees of smoothness or roughness of the different scale intervals Helmholtz constructed a diagram similar to that shown in Fig. 77. Consonance is indicated when

the wavy line touches the horizontal line, while roughness or dissonance is proportional to the divergence of the two lines. Thus perfect consonance appears at *c*, *f*, and *g*, slight dissonance is evidenced at the major third and sixth *e* and *a*; while the increasing dissonance reaches a maximum near either *c*.

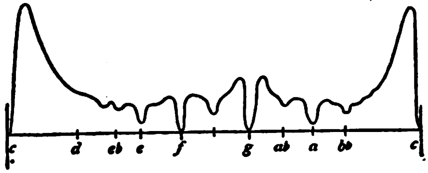


Fig. 77.

Graphic illustrations of beats.

Lissajous (1822-1880) invented an apparatus in which small mirrors attached to a couple of tuning-forks were so located as to throw upon a screen the combined motion of the forks, with the result that curves were reflected that were simple or complex according as the interval between the forks was consonant or dissonant. In a similar device invented by Koenig, shown in Fig. 78, one of two electrically-excited forks bears upon its prong a piece of smoked glass upon which a style on a prong of the other fork is made to trace a record as the latter fork is moved along at right angles to the former. Some of the results with forks of varying frequencies are shown in Fig. 79, unison forks giving the simple curves of the first example, the octave next shown imparting a twist to the figures, which are much dis-

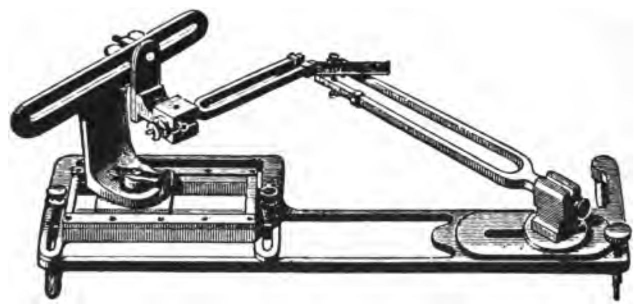


Fig. 78.

turbed as the octave is put slightly out of tune in the third example. The major third and the half step shown in the

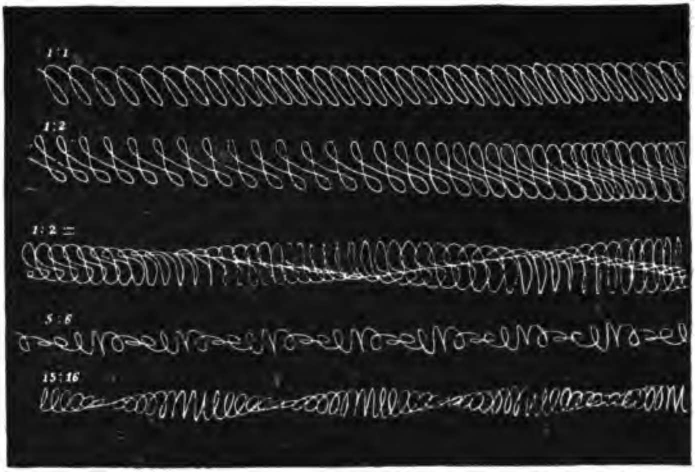


Fig. 79.

fourth and fifth examples display the expected growth in intricacy.

Nature of triads.

A *chord* in music results from the combination of three or more tones. Two thirds joined by a common tone make a *triad;* and this triad is consonant when not only the individual thirds are consonant, but also the fifth produced by their union. Only two distinct triads of this nature are possible in our musical system: the *major,* in which the lower third is major and the upper minor, and the *minor,* in which these positions of the thirds are reversed. In both cases the fifths are perfect. Three positions of each triad are recognized, according as either note is placed beneath the others. Since, also, the triad tones may be located in different octaves and may be reduplicated at will, there is much possible variety in their combination.

From a study of the resultant tones Helmholtz selected six combinations of the major triad as most perfect and six as less

Combinations of triad tones.

perfect. These are shown in Figs. 80 and 81, the resultant tones appearing as black notes. No

Fig. 80.

Fig. 81.

combination of the tones of the minor triad was found free from discordant resultant tones, so that the three best positions are those of Fig. 82.

Fig. 82.

The major and minor triads form the basis of our harmonic system, since they are the chief means of establishing tonality and furnishing points of repose. By adding other thirds to these, chords of the *seventh, ninth, eleventh,* and *thirteenth* are built up, all of varying degrees of dissonance. Modern musicians display their skill by the continuous use of such indeterminate chords to weave a web of logically-dependent but constantly-shifting harmonies which sometimes delays the conclusive consonance until the very end of the composition.

Other chord formations.

Reverting now to the formation of the scale, let us consider some of the difficulties which arose when the "just" scale was applied to keyboard instruments. Evidently, in order to modulate from one scale-key to another it should be possible to reproduce exactly in the second key all the intervals of the first. To

Difficulties in the use of the "just" scale.

play all intervals in just intonation even in a single scale-key, however, requires two extra keys in each octave; for while in the scale of *C*, for instance, the fifths *C-G*, *E-B*, *F-C*, and *A-E* are true, *D* is a comma too sharp for the true fifth *D-A*, and also a perfect fifth from *B* needs an additional tone, *F*♯. With each new scale there must be similar adaptations of the intervals, so that, in order that there may be unrestricted modulation, an instrument must have at least seventy-two keys to each octave!

Systems of "tempering."

Accordingly, many attempts were made to reduce the number of keys by slightly mistuning or *tempering* certain tones and thus identifying them with others of nearly the same pitch. Two systems based upon this principle, each of which employs but thirteen keys to the octave, especially claim our attention.

Mean-tone temperament.

In the first or *mean-tone temperament*, the upper tones of all the fifths in the ascending circle (page 92) are flatted a quarter of a comma each. The purity of the major thirds is thus preserved, so that conditions result exactly the opposite of those in the scale of Pythagoras (page 92), which kept the fifths true while mistuning the major thirds. By using this system tolerably pure intonation is possible in six scale-keys, but modulation into the remaining scale-keys is impossible since their major thirds are hopelessly out of tune. Nevertheless the mean-tone temperament had a wide vogue, and was employed for organs even to the middle of the last century.

Equal temperament.

In the system of *equal temperament* now in general use the octave is divided into twelve such parts that each bears the same ratio to every other. In consequence, every interval is slightly mistuned except the octave. But, on the other hand, a great advantage is gained in the fact that an entirely free interchange of scale-keys is made possible, since a scale of precisely the same intervals can be constructed from each tone as a basis.

In Fig. 83 the discord due to temperament is shown on

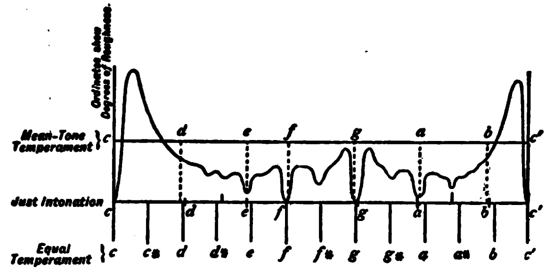


Fig. 83.

Helmholtz's diagram. The positions of tones in *just intonation* are indicated by short verticals on the lower horizontal line; those of the tones in *mean-tone temperament* by the dotted verticals; and those of the tones in *equal temperament* by the long verticals below.

Comparison of different systems.

Although recognizing its availability scientists for a long time opposed the general adoption of equal temperament on account of its mathematical inaccuracy, regarding it as simply a make-shift until something better could be devised. Musicians generally, however, from Bach onward, have hailed it with acclaim, recognizing its enormous possibilities in the direction of added musical resources. They have pointed out that scales are chosen essentially for æsthetic effect, and that this effect should not be fettered by mere mathematical considerations. Unquestionably the opening of the door to unrestricted shifting of tonality has been the cause of the wonderful advance in musical expression during the past two centuries; and in view of this development the slight deviation, scarcely perceptible even to expert ears, of the equally-tempered scale from the theoretical tones seems almost negligible.

Attitudes toward equal temperament.

Then, too, the adoption of a standard scale for all musical uses is of great advantage. It has been suggested that music in its purely vocal forms or as rendered by the string quartet should be kept in just intonation. But keyboard instruments are now so closely

Advantages of a uniform scale.

connected with all other forms of music production as to make the adoption of an altered intonation for special situations well-nigh impossible. Orchestral instruments of fixed pitch are accordingly tuned to the equally-tempered scale, to which the players of stringed instruments conform without difficulty. Indeed, absolute adherence to just intonation is not easy for violinists, who so far violate scientific conclusions as habitually to play a sharp tone, such as *F*♯, higher in pitch than its corresponding flat tone, or *G*♭. With singers alone, therefore, is just intonation optional; and, owing to the prevalence of accompanied vocal music, it is doubtful if many take advantage of the privilege. Certainly, until theorists furnish something palpably better, the equally-tempered scale will continue to justify its name by pursuing its way serenely amid the many adverse criticisms with which it has been assailed.

SUMMARY.

Scales have been formed somewhat arbitrarily, although the characteristics of a scale are generally found within the compass of an octave, and the intervals of a whole step, a perfect fourth and a perfect fifth are frequently recognized.

By the word *interval* we mean the ratio between the vibration numbers of two tones.

The Greek system of diatonic scales was followed out in the early scales of the Christian Church. These latter were finally superseded by our major and minor scales, the intervals of which were fixed by theorists in accordance with the assumption that consonance is produced by simple vibration ratios.

Helmholtz was the first to explain the reason for this doctrine by showing that consonance and dissonance are dependent on the absence or presence of disagreeable beats.

The major and minor triads are the only consonant chords in our musical system, and therefore the only ones expressing finality. They are employed in a variety of combinations, of which but few are theoretically perfect in their consonance.

"Just" intonation is impracticable for keyboard instruments because of the impossible number of keys required to preserve the purity of all intervals. The system of mean-tone temperament was long prevalent, but was finally superseded by that of equal temperament.

REFERENCE LIST.

Helmholtz, Parts 2 and 3.
Zahm, Chapter 10.
Barton, Chapter 9.
Harris, Chapters 5, 14-17.
Broadhouse, Chapters 13, 15, 16.
Pole, Parts 2 and 3.
Lavignac, Chapter 1, D.
Barnes, Chapters 13, 14, Appendix 2.
Catchpool, Chapter 7.

Stone, Chapter 7.
Poynting and Thompson, Chapter 10.
Tyndall, Chapter 9.
Blaserna, Chapter 7.
Taylor, Chapters 8, 9, 10.

CHAPTER VIII.

THE EAR AND THE VOICE.

Human organ of sound.

TWO of the organs of the human body are intimately related to the phenomena of sound. The first of these, the *ear*, collects the sound-vibrations from the surrounding atmosphere and transmits them to our consciousness; while the second, the *voice*, is by far the most wonderful known instrument for tone production. Without the organ of hearing all the external movements which have been described would exist for us in vain, and we should live in a silent world, while without the voice the communication of thought by speech and the outpourings of the soul in song would be impossible.

Three divisions of the ear: first, the outer ear.

If we examine that marvelously delicate organism, the ear, we will discover that it embraces three well-defined sections, which may be called respectively the *outer*, the *middle*, and the *inner* ear. Of these the simplest to understand is the outer ear. This comprises, first, the shell-shaped, cartilaginous *lobe* (Fig. 84, *L*), which receives the sounds in much the same way as does the bell of a trumpet. Leading from the lobe inward and slightly forward is the somewhat crooked tube of the *auditory canal* (Fig. 84, *AC*), about 1¼ inches long, of which the wall is of cartilage for nearly half its length and of bone the rest of the way. A number of fine hairs and the ear-wax secreted by glands within protect this from the intrusion

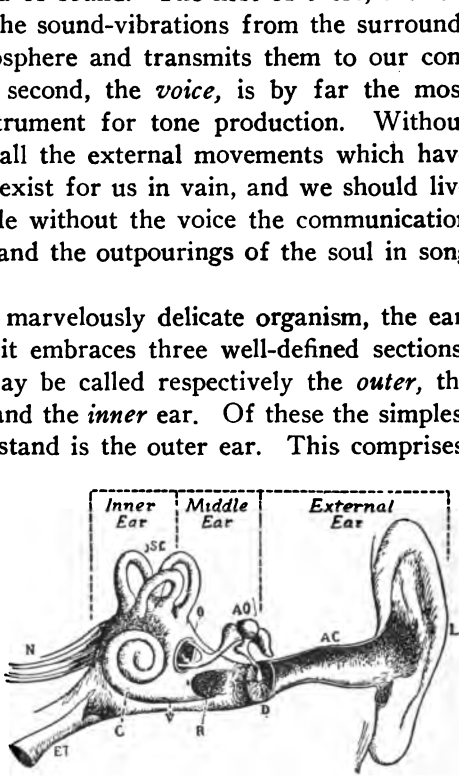


Fig. 84. Transverse section of the ear.

of external objects. At the end of the canal, stretched slantwise and curving inward, is the thin, elastic membrane known as the *drumskin* (Fig. 84 *D*), which, like the diaphragm of the telephone and phonograph, is quick to respond to every kind of sound-wave which impinges upon it.

The middle ear.

Behind this membrane is the middle ear or *drum cavity,* hollowed out in the thick bony part of the skull. On the side of this cavity opposite the drumskin are two so-called *windows,* each of which is covered also by a membrane. The lower of these, the *round window* (Fig. 84 *R*) is about the size of a pin's head, while the upper or *oval window* (Fig. 84 *O*) is somewhat larger. In the lower wall of the cavity is an opening from which the *Eustachian tube* (Fig. 84 *ET*), 1½ inches in length, leads to the back of the throat. Whenever we swallow, this tube is opened, so that the drum cavity is kept in touch with the external air, and thus relieved from undue pressure. We can appreciate the need of this outlet when we experience the sensation of deafness and roaring in the ear which results from the clogging of the tube that sometimes occurs in the progress of a "cold in the head."

The auditory ossicles.

Three peculiarly-shaped bones called the *auditory ossicles* (Fig. 84 *AO*), which have been named from their fancied resemblance to familiar objects, form a chain of connection between the drumskin and the oval window. These are shown more specifically in Fig. 85. The lower part of the *hammer* is attached directly to the drumskin, pulling it slightly inward, while the upper part articulates with the *anvil.* This bone in turn is attached on its lower side to the apex of the *stirrup,* of which the base is fastened to the membrane of the oval win-

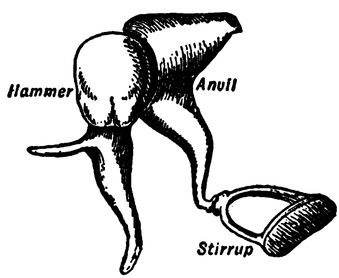


Fig. 85.

dow. All these bones together form a kind of lever which reproduces every motion of the drumskin in the membrane of the oval window, with this difference, however, that in transmission the vibrations are diminished in magnitude but increased in force. As the membrane of the oval window is but $\frac{1}{15}$ to $\frac{1}{20}$ the size of the drumskin, this lessening of magnitude becomes necessary, while the greater force is required to overcome the added density of the medium on the other side of the oval window, to which the vibrations must next extend. We should also mention two important muscles contained in the drum cavity, which have the power of tightening the membranes respectively of the drumskin and of the oval window.

General form of the inner ear.

It is the inner ear, however, which contains the most important and complicated section of the hearing apparatus; indeed, if all the mechanism of the external and middle ear were destroyed, it might yet be possible for a person to hear, in part at least, by holding between the teeth some such device as that mentioned on page 6, which transmits the sound through the bones of the head. The inner ear occupies a complex bony cavity which is so winding in its course that it is called the *labyrinth.* Within the outer or *bony labyrinth* there is a membranous sack called the *membranous labyrinth,* which follows approximately the curves of the bony labyrinth and is only connected with the latter where the nerve fibres pass between them. These fibres ramify over the surface of the membranous labyrinth, and are excited by minute hairs which project from the delicate inner lining of the membrane, and which are themselves set in motion by *otoliths,* or minute solid particles like grains of sand. These particles are floating in a watery fluid called the *endolymph,* which fills the membranous labyrinth, and the latter is nearly surrounded by a similar fluid called the *perilymph.*

This perilymph is in direct contact with the oval window of the middle ear in the *vestibule* (Fig. 84 *V*) which forms the

entrance to the inner ear and also the centre of its structure. Branching upward and backward from the vestibule are the three so-called *semi-circular canals* (Fig. 84 *SC*), which have five openings into it. These canals are believed to be the seat of the sense of equilibrium, and are therefore not intimately concerned with our discussion of the sense of hearing.

The vestibule and semi-circular canals.

It is in the *cochlea* (Fig. 84 *C*), situated forward and downward from the vestibule, that sound-perception is especially located. This cochlea (meaning "shell") is named from its resemblance to a snail-shell. It consists in a tube which winds two and one-half times around a central bony axis and terminates in a closed tip. A bony partition called the *lamina spiralis* projects into the tube for about two-thirds of its diameter, the other third being spanned by a membrane called the *basilar membrane*. This partition ends just before the tip of the tube is reached, so that the tube is divided through nearly its entire length into two chambers, the *scala vestibuli* and the *scala tympani*, that are filled with the perilymph and that communicate at the tip of the tube. One of these chambers opens into the vestibule while the other is directly connected with the membranes of the round window. The latter thus serves as a kind of buffer for the vibrations which, be-

Divisions of the cochlea.

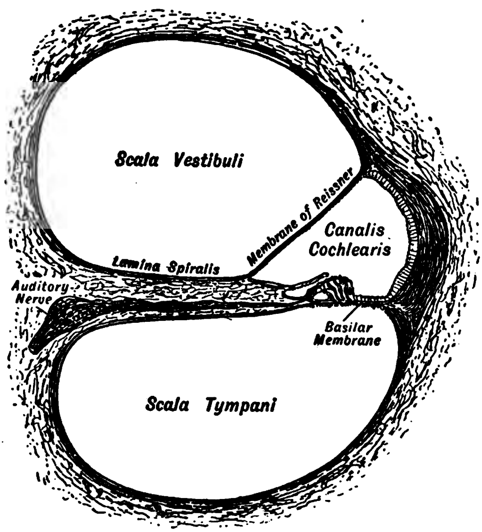


Fig. 86. Transverse section of the whorl of the Cochlea.

ginning at the vestibule, travel up one of the chambers and down the other, and which would otherwise be deadened by the lack of a yielding surface from which to rebound. A small canal containing endolymph is formed by the *membrane of Reissner,* which extends from the *lamina spiralis* to the outer wall of the tube. The positions of all these parts can be better understood by reference to Fig. 86, which shows a transverse section of the cochlean tube.

In the region of the basilar membrane a very complex structure is found. The outer portion of this membrane is composed of at least 3000 radial fibres imbedded side by side and growing longer from the entrance of the tube to its tip, so that at the latter end they are ten times as long as at the former. It is thought that these fibres are tuned to the various degrees of sound-waves, so that these waves sweeping over them set into sympathetic vibrations the fibres which agree with the waves in pitch, and which then vibrate with an intensity proportionate to that of the exciting force. While thus *pitch* and *intensity* are determined, *quality* results from the combination of the diverse sound-components.

Fibres of the basilar membrane.

Intermediary agents between these fibres and the auditory nerve which enters at *N,* Fig. 84, and which winds its way through the *laminar spiralis,* are the *organs of Corti,* two ranks of fibres at the base of the basilar membrane, which lean over against one another like the rafters of the peaked-roof of a house. Nerve cells surround these fibres both on the exterior side and in the canal between.

The organs of Corti.

The exceeding delicacy of the structure of the cochlea can be estimated when we reflect that its entire coil has a diameter of but one-quarter of an inch, and that if unrolled its length would be about 1½ inches. Fig. 87 gives an enlarged sectional view of the inside of the ear, showing the proportions of the parts. As in Fig. 84, *AC* is the

Dimensions of the cochlea.

auditory canal, *D* the drumskin, *AO* the auditory ossicles, *ET* the Eustachian tube, *O* the oval window, *R* the round window, *SC* the semicircular canals, and *C* the cochlea.

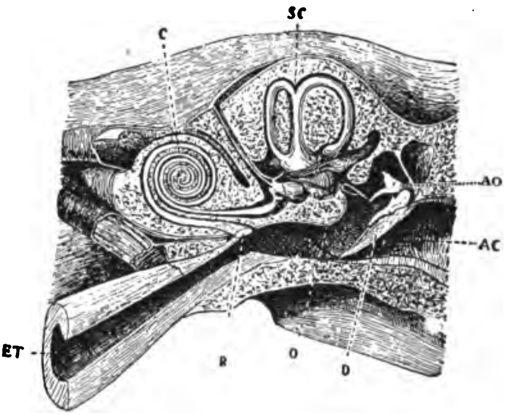


Fig. 87. Section of the middle and inner ear.

A sound-wave striking the outer ear thus makes its way through the auditory canal and sets into vibration the drumskin, whence it is carried by the auditory ossicles to the oval window. The increased force which it gains in this transmission suffices to set into motion the perilymph in the vestibule of the inner ear, which in turn conveys it around the curves of the cochlea until it discovers and sets into vibration the proper membranous fibre. Through the organ of Corti the impulse strikes the auditory nerve which carries it to the brain, whence, in some inexplicable manner, it passes into our consciousness.

Course of a sound-wave through the ear.

Four factors are involved in voice-production, namely, the *lungs,* which act as the *motor,* the *vocal cords* or *vibrator,* a number of cavities which constitute the *resonator,* and a mechanism for modifying or checking the tone called the *articulator.*

Factors in voice-production.

Nearly the whole of the chest cavity is occupied by the *two lungs.* When these are expanded the outer air is drawn into them in *inspiration,* and when they are contracted the air is forced out in *expiration.* In the latter process the air passes from the lungs through the

The lungs and wind-pipes.

windpipe, a cartilaginous tube four or five inches long, into the *larynx,* there coming into contact with the vocal cords.

The larynx.

The *larynx* or *voice-box* is a triangular tube composed of several pieces of cartilage, the front edge appearing in the throat as the familiar "Adam's Apple." Within this tube, stretching from front to back, are the two folds of membrane known as the *vocal cords.* These are attached to the outer walls, and are free only on their inner sides, where there is consequently an opening, called the *glottis.* By means of a number of muscles which act automatically, the vocal cords may be expanded or contracted in

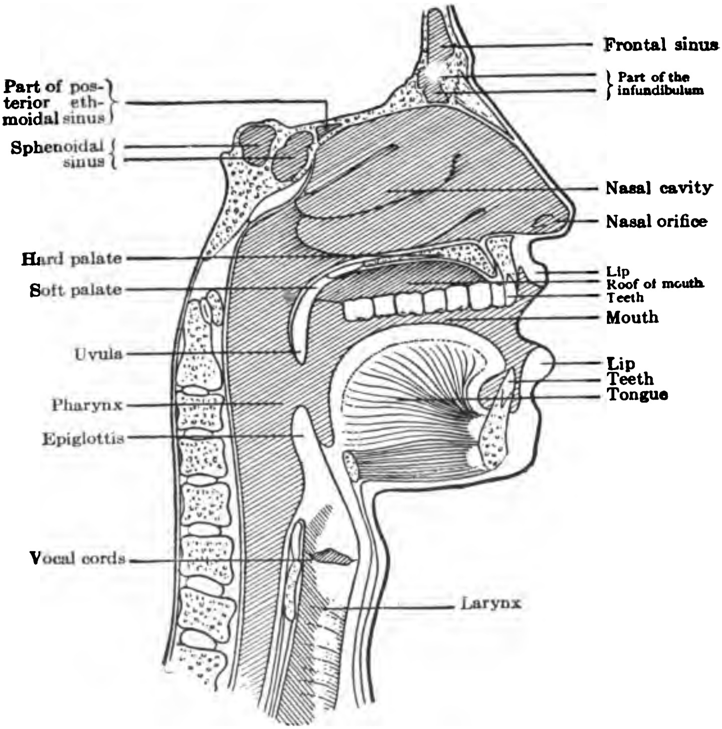


Fig. 88. Section of the head and throat locating the organs of speech and song, including the upper resonators. The important maxillary sinus cannot well be shown. It is found within the maxillary bone (cheek bone). The inner end of the line marked *Nasal cavity* locates it.

a variety of ways, and the "chink of the glottis" may be widened, shortened, or narrowed until it is entirely closed.

In ordinary breathing the vocal cords remain wide apart, so that the air passes between them freely. When, however, tone is desired, the cords are brought together so that the air is expelled in a multitude of little puffs, as with a reed. These puffs generate a tone which, though feeble, is yet sufficient to set the resonating cavities into sympathetic vibration. The loudness of the tone is affected by the amount of breath pressure on the vocal cords, and the pitch is determined by their tension and position relative to each other.

Action of the vocal cords.

We have now to consider the *resonating cavities,* the shape and adjustment of which have so important an effect on the quality and quantity of tone. Reference to Fig. 88 will make the positions of these clear. At the top of the larynx is a *lid* or *epiglottis,* which closes it in the act of swallowing and also aids in developing the generated tone. Next comes the cavity at the back of the mouth called the *pharynx,* which may be changed materially in shape by muscular action, and the walls of which come together when swallowing takes place. If the pharynx is kept as far open as possible its resonance greatly enriches the vocal tone. Into it open the two Eustachian tubes connecting with the ears (page 109).

The epiglottis and the pharynx.

Two passages from the pharynx lead the one into the *mouth cavity* and the other into the *nasal cavities.* The *soft palate* terminating in a pendulous tip called the *uvula,* which can readily be seen hanging down in the back of the mouth, regulates the size of these openings. If the soft palate be forced backward until the passage to the nasal cavities is closed, vibrations are communicated to the latter only through the palate, so that a muffled "nasal twang" results. When, however, the palate is allowed to hang freely, with only such changes in position as are necessary to keep the cavities in tune with the generated tone, resonance is un-

The soft palate.

restricted and the tone vibrates through the cavities of the nose and head.

The roof of the mouth, or *hard palate,* with the soft palate behind it form the floor of the two nasal cavities. These are separated by the bony partition which forms the bridge of the nose, and into each one project three spongy bones which serve to increase the surface area. This surface is lined throughout with mucous membrane covered with continually moving hairs or *cilia,* by means of which the air entering the nostrils is purified, tempered and moistened before proceeding to the lungs.

The nasal cavities.

A number of air-chambers or *sinuses* are hollowed out in the bones beside, above and behind the nasal cavities. As these possess passages of communication with each other and with the nasal cavities, they form valuable adjuncts to the resonating resources. Since the nasal and head cavities cannot be changed in form, their resonating powers will be determined by their natural size and shape and their freedom from obstructions.

The sinuses of the head.

While the nasal and head cavities are the chief factors in producing strength and purity of tone, the mouth cavity and its adjacent parts have as their distinct function the modifications of the tone in *articulation.* A dome-shaped roof consisting of the *hard palate* surmounts the mouth, bounded in front and on either side by a row of teeth which furnish resistance to the tongue and lips in forming consonants. The free lower jaw, furnished with a correlative row of teeth, renders mobile the tongue, which is attached to it directly by muscles and indirectly by the *hyoid* or *tongue bone.* Evidently a relaxed lower jaw and flat tongue favor resonance by enlarging the mouth cavity.

The mouth.

During articulation there is a constant muscular interplay between the tongue and the teeth, which by their varied positions modify or interrupt the tone to produce most of the effects which we translate into words.

Articulation.

Changes in the shape of the mouth cavity as a whole are

responsible for the tone-qualities known as *vowel sounds*. Experiments have proved that each vowel has a normal pitch which is, moreover, the same for all voices. That of *oo* is the lowest and that of *ee* the highest, the others ranging between these limits, with *ah* occupying a middle position. Each vowel-characteristic may, however, be extended up and down from its normal pitch, although certain pitches are more favorable than others. *Oo* and *oh*, for instance, are more easily sung at a low pitch and *ai* and *ee* at a high one, while *ah* lends itself readily to the entire compass.

Nature of the vowels.

Vowel-quality is modified in a variety of ways by *consonants*, which are really forms of obstruction to the simple vowel sounds. Besides the tongue and lips, the organs of articulation, by which these obstructions are effected, include the teeth and the hard and soft palates, while the facial muscles may also be called into play as an aid in the process. According to a classification that is useful for singers the consonants may be grouped as follows:

Nature of consonants.

1. the *explosives*, such as *p, t, f, v*, in which the obstruction is complete;
2. the *semi-explosives*, such as *b, d*, and hard and soft *g*, in which the obstruction is only partial;
3. the *permanents*, like *l, m*, and *n*, of which the sound can be prolonged indefinitely.

The aspirate sound of *h* is formed by allowing the breath to flow through the glottis before the tone is produced.

Another classification groups the consonants according to the place in which they are produced: for instance, *m, b, p*, made with the lips, are termed *labials; t, d*, and *n*, formed by pressing the tongue against the teeth are *dentals;* and those like *k* and hard *g*, made in the back of the mouth, are *gutterals*. These consonant sounds are also used in a number of combinations.

Labials, dentals and gutterals.

There is no considerable difference in the formation of tone for the speaking and singing voice. In the former, since distinctness of utterance is the

Speech and song.

prime requisite, the tone-compass is narrow and the tone unsteady, while in the latter definite pitches are assumed throughout the natural voice compass. "Speech may be called the prose, and song the poetry of vocalization."* Singers often make the mistake of unduly modifying vowels and clipping consonants in order to produce purity of tone, thus defeating the primary object of song, which is to give a fuller expression to the meaning of the text.

Besides the sounds of vowels and consonants, all kinds of tone-qualities, both good and bad, are possible to the voice.

Graphic vocal tones. Professional imitators, indeed, are able to produce a recognizable vocal suggestion of almost any sound whatever. Some attempts have been made to secure graphic representations of vocal tones, so that practical means may be provided for measuring their degree of conformity to a given standard. Mrs. Watts Hughes, of London, published a pamphlet in 1891 recording various experiments with an instrument which she calls the *Eidophone.* This consists of a long tube having the large end bent upward. Over this end a membrane is stretched on which is strewn light, pasty materials which, when tones are sung into the other end, range themselves into constantly-varying shapes, whose complexity is dependent on that of the tones to which they respond. Besides geometric figures, delicate flower, tree and shell designs are formed, such as those shown in Figs. 89, 90 and 91. Recently, also, by a similar device in which the vibrations of a rubber disk are reflected by an attached mirror upon a rapidly-moving sensitive plate, Dr. Mirage, of Paris, claims to have secured

Fig. 89. Daisy form

*Fillebrown—"Resonance in Singing and Speaking."

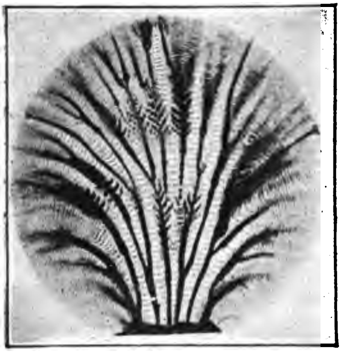


Fig. 90. Fern form.

photographs of the voice which show marked distinctions between true and false intonation.

Range of voices.

All the tones produced by the human voice cover nearly four octaves, although these limits have been considerably extended by exceptional singers. Average voices have a range of somewhat less than an octave and a half, and in men this compass is about an octave below that in women. The latter fact is due partly to the difference in the formation of the resonance chambers and partly to the di-

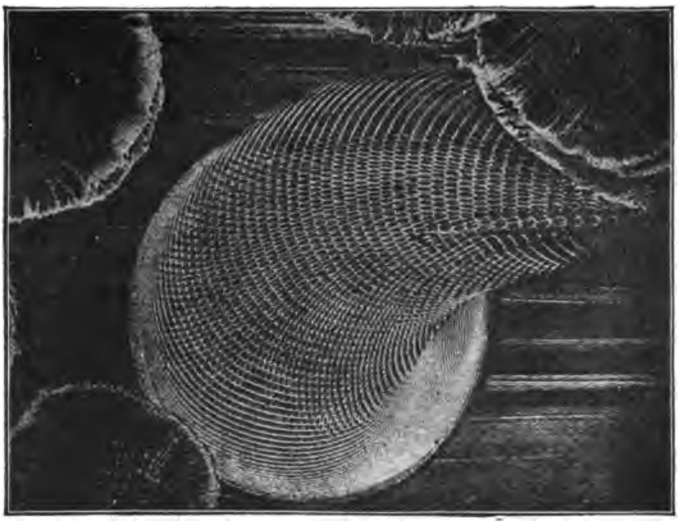


Fig. 91. Shell form.

versity in the thickness and extent of the vocal cords, those of men averaging three-quarters of an inch and those of women

a half inch in length. Voices are classified chiefly according to their quality, so that singers whose best tones are high in pitch rank as sopranos or tenors, those who excel in the middle tones are called mezzo-sopranos or baritones, while the low voices are classed as altos or basses. Voices of extreme range are rare, for the average human voice is of middle range. Fig. 92 shows the normal limits of the various kinds of voices.

COMPASS OF THE SINGING VOICE

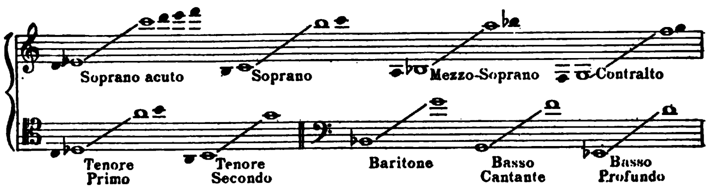


Fig. 92. Compass of the singing voice.

SUMMARY.

THE ear has three sections, of which the outer comprises the *lobe* and the *auditory canal,* leading to the *drumskin.* Sounds are transferred from the drumskin in the middle ear by means of the three *auditory ossicles* to the *oval window,* which closes the entrance to the inner ear. In the latter the *bony labyrinth* is filled with a watery fluid containing the *membranous labyrinth,* and by a complicated arrangement in the *cochlea,* sound is communicated to the *auditory nerve,* which conveys it to the brain.

There are four factors in the voice. The first of these is the *lungs,* which as *motor* furnish the breath supply that sets into motion the second factor or *vibrator,* consisting of the *vocal cords.* The tone which they produce is greatly magnified and altered in quality by a number of *resonance chambers,* which form the third factor. Tone emerges from these as vowel sound, which may be more or less obstructed by the consonant sounds originated by the fourth factor, namely, *the organs of articulation.* Individual voices differ markedly in quality and compass.

REFERENCE LIST.

THE EAR.

Helmholtz, Chapter 4.
Tyndall, Chapter 9.
Barton, Chapter 6.
Catchpool, Chapter 7.
Harris, Chapter 3.
Lavignac, Chapter 1, C.

THE VOICE.

Helmholtz, Chapter 5.
Broadhouse, Chapter 10.
Barton, Chapter 8.
Lavignac, Chapter 2, A.

The following books on singing have valuable data concerning acoustics:

Fillebrown, "Resonance in Singing and Speaking." (Oliver Ditson Company, 1911.)

Curtis, "Voice Building and Tone Placing." (D. Appleton and Company, 1909.)

Browne and Behnke, "Voice, Song and Speech." (G. Putnam's Sons, 1883.)

Standard medical works, like Gray's Anatomy and Waller's Physiology may be consulted for more minute details concerning both organs.

CHAPTER IX.

Musical Instruments.

While the voice, most marvelous of all instruments, has been the common property of all men in all ages and climes, artificial instruments have taken on so endless a variety of forms that a mere catalogue of them would fill a large volume. We shall content ourselves, therefore, with examining the most important of those of the present day, and with studying simply the acoustic peculiarities of these, leaving to specialized works the treatment of minute details of their construction and technic. For the most part, instruments have assumed their final shapes as the result of many experiments, in which scientific theories have played but a small part. When viewed in the light of acoustic laws, however, they have almost always been found to conform to these laws and to furnish interesting examples of their practical application.

Variety in the construction of instruments.

One kind of instrument is distinguished from another by the *materials* of which it is made, its *form, compass, sustaining power, degrees of possible intensity,* and especially its *quality*. Again, some instruments are restricted to the production of one tone at a time, while on others, like the violin and piano, tonal combinations are possible. As with the voice, each instrument must have a *motor* for exciting it into action, a *vibrator* generally accompanied by a *resonator,* and a *mechanism for regulating the pitch and other characteristics of the tone.*

Characteristics of instruments.

With all their diversity, instruments are readily divisible into a few well-defined types. Foremost among these, on account of their wide range, facile manipulation and general availability, stand the *instruments with stretched strings*. Let us first discuss those

Types of instruments: those with strings.

of this class in which the strings are ***plucked,*** either by the fingers or by a device called a ***plectrum.***

A weak-toned instrument chiefly used for accompaniments is the *guitar.* This has six strings, the three upper of catgut

The guitar.

and the others of silk wound with silver wire, tuned thus:  Its notes are always written an octave higher than played. The strings are plucked by fingers of the right hand while those of the left vary the scale-notes by pressing the strings against metal bars or *frets* which cross the neck at the proper intervals. Upper partials or "harmonics" can be played by touching the strings lightly, instead of pressing them upon the frets, at one of their nodal points.

The guitar often accompanies the *mandolin,* a pear-shaped instrument also fretted and having eight strings tuned in

The mandolin.

unison pairs to the same tones as those of the violin, thus:  A plectrum of horn or tortoise-shell held in the right hand excites the strings. While, as with all stringed instruments, the inferior limit of the compass is the tone of its lowest string, the upper limit for the mandolin is about e''', an octave above the tone of its highest open string. Bright upper partials give a nasal quality to the tone, which is, however, light and delicate in character.

By far the most important instrument of this group is the *harp,* which has a large range and an ethereal tone that is fre-

The harp.

quently employed with much charm in orchestral combinations as well as for solo work. Its 46 strings are tuned diatonically in the scale of $C\flat$ through a compass of 6½ octaves, which extends from $C\flat'$ to $f\flat^{iv}$. By means of seven pedals, each of which may raise a given tone a half or whole step throughout the compass, the tuning may be "set" for any major or minor scale other than the original one. Running passages in broken chords, called *arpeggios*

from the instrument itself, are characteristic of the harp. By touching a string lightly in the middle with the palm of the hand and plucking it with the first two fingers of the same hand, clear and beautiful harmonics are evoked.

Their resonators.

In the case of the guitar and mandolin the natural tone of the strings is strengthened by sympathetic vibration of the body of the instrument and the air within it, while with the harp a similar effect is gained by the sound-box on which it stands, and which acts as a resonator.

The pianoforte.

Instruments with *struck* strings have as their chief representative the hard-worked *pianoforte*. Eighty-eight strings of different pitches, of which all but the very lowest are doubled and many are trebled, extend at semitone distances over a compass of $7\frac{1}{3}$ octaves, from A_{II} to c^{v}. Their tones are reinforced by a thin, flat sounding-board. Felt-covered hammers are driven against the strings by a key mechanism, to induce vibration, and by the elastic covering and rounded ends of these hammers the metallic overtones are suppressed which are produced when a hard object strikes a string at a single point. By making each hammer attack its string at $^1/_7$ or $^1/_9$ of its length from the end, other disagreeable upper partials are avoided (page 58).

Quality of tone.

The soft pedal, by moving the action along in the "grand" piano, causes each of the hammers to strike on one less string than it does normally. Sympathetic vibrations in the string thus left free give a peculiarly delicate flavor to the tone; otherwise the piano tone is susceptible of little variation in quality. Its availability as a household instrument, its power of suggesting harmonically all forms of music, its usefulness for accompaniments and its large repertory of important solo compositions account for the wide popularity and influence of the piano.

All the instruments thus far studied give tones of an *explosive* character, since the vibrations of the strings rapidly die away after their first impulse; hence the performer has no

Means of stopping vibrations.

direct power of sustaining a tone and can only suggest this imitatively, as by rapidly repeating the given impulse. Since the harp and piano tones, although greatly weakened, yet continue for some time after the strings have been excited, means for stopping the vibrations must be provided to prevent confusion of sounds. The harpist accomplishes this result by laying the palms of his hands on the strings immediately after they are sounded; while, in the piano, dampers connected with the individual keys descend upon the strings when the keys are released, except when all these dampers are suspended by the mechanism of the so-called "loud pedal." Although the office of this pedal is thus primarily to allow a tone to continue, its use also results in the reinforcement of a given tone by the partials of other strings in unison with it.

Bowed instruments.

Of all manufactured instruments those played with a bow allow the performer the most absolute command over the tone which he produces. Hence in the development of the orchestra the "strings," as they are popularly called, soon took first place, resolving themselves into the four forms which are employed at present, the *violin, viola, violoncello* and *double bass.*

The violin.

Considering first the violin, as the most important member of this family (Fig. 93) we find that it has four strings, the three upper of plain gut and the lowest wound with fine wire.

They are tuned thus:

Fig. 93. Violin.
Length, 23½ in.; length of bow, 29½ in.

Brilliant and ethereal tones are produced from the highest string, the others diminishing in vividness, and the lowest having a rich and sombre quality. Vibrations are induced by the rosined horse-hairs of the bow, and are communicated through the bridge to the resonating body of the instrument. The air within this also serves as a resonator, as may be proved by blowing across one of the two vents called "F holes." Many violins are found to possess special resonance for one or two tones, although this property is not considered desirable.

Its fingering.

Different scale-tones are obtained, as on the guitar and mandolin, by pressing the strings upon the finger-board with the fingers of the left hand; but in the case of the violin the absence of frets at once makes greater demands upon the musical sense of the performer and at the same time opens greater possibilities in the direction of sliding from one tone to another or slightly varying the pitch of a tone. The latter effect is used in the *vibrato,* made by oscillating the finger to and fro on the string.

Its compass.

The normal range of the violin is about 3½ octaves, extending to c^{iv}. This range may be pushed somewhat further by the use of *harmonics,* which result from touching the string at nodel points instead of pressing it down.

Tonal possibilities.

Several conditions contribute toward the quality of the violin tone. Purity is favored by drawing the bow straight across the string, since lengthwise vibrations, otherwise excited, introduce "scratchy" elements. In light passages the bow is held obliquely, so that only the hairs on one edge touch the strings, while in *forte* passages the tone is increased by bringing more of the hairs to bear upon them. The speed and pressure of the bow are also determining factors, as is its location on the string. Bowing near the bridge produces brilliant overtones, while the quality grows softer and more flute-like as the finger-board is approached. Ordinarily a position about an inch from the

bridge gives the best results. Roughness of the bow or imperfections in the structure of the violin may seriously impair the quality of tone. Even an expert violinist cannot produce satisfactory results from a poor instrument. On the other hand, a violin made skillfully of fine materials, such as well-seasoned woods and enduring varnish, should continually improve with proper usage, as its resonance becomes more perfect. By affixing a small notched clamp of metal, called a *mute,* to the bridge, the vibrations are impeded and a soft, veiled quality is imparted to the tone.

Variations in structure of strings.

It is important that the constituents of all the violin-strings should be alike, so that no part of one is different from a corresponding part of another, since the fingering for whole and half steps would otherwise vary on different strings. So long as all the strings alike become thinner where the bow is drawn across them, for instance, the relative distances remain constant, but if a string breaks and a new one is inserted which is not worn as are the others, difficulty will be found in playing in tune. Hence skilled performers often replace the whole set of strings when one of them breaks.

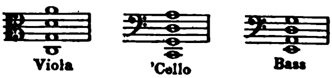
Special effects.

Single tones are made possible by the rounded form of the bridge. Two strings side by side may be sounded together, but when three or four tones are to be combined arpeggiating is necessary. A tone may be sustained for any amount of time, and may be increased or diminished in power while sounding. Many kinds of *legato* and *staccato* can be produced, while there are special effects like the *tremolo* or shivering of the bow on the strings and the *saltando* or jumping bow. In the *pizzicato* the violinist plucks the strings with his fingers.

Characteristics of the other strings.

Most of what has been said regarding the violin applies also to the other orchestral stringed instruments. Headed by the first and second violins, the tone descends through the violas, violoncello, and double basses. Each of the last-named instruments has four

strings, except that in England the double bass frequently has but three. The tuning is as follows:



Notes for the double bass are written an octave higher than they are played, hence the open strings sound an octave lower than is indicated above. On account of the long finger stretches the double bass is tuned in fourths instead of fifths as are the others. Harmonics are used somewhat sparingly on the

Fig. 94. Violoncello
Length, 4 ft.; length of bow, 28 in.

Fig. 95. Double-Bass.
Length, 6 ft. 6 in.; length of bow, 23½ in.

viola and violoncello, but are harsh and unmusical on the bass. The latter retains the old viol form of a flat back and sloping shoulders, while all the other strings have high shoulders and arched front and back. Mutes are employed with the viola and violoncello, but are impracticable for the bass, on account of their necessarily large size.

The viola.

The *viola* stands toward the violin in the relation of alto to soprano. Its thicker strings give a fuller and more penetrating tone than that of the violin, and while its range is about three octaves, extending to c''', its highest tones are seldom heard. It is not ordinarily used alone, but occasionally renders individual passages with finely expressive effect.

The violoncello.

On the other hand, the *violoncello* (Fig. 94) is especially distinguished as a solo instrument. It is used throughout its orchestral range, which extends to about e'', although this limit may be considerably extended; and in the orchestra it sometimes soars even above violas and violins. The strength and richness of its tones make it valuable for melodic expression, while under the fingers of a skilled player it may render rapid passages with great brilliancy.

The double bass.

To the *double bass* (Fig. 95) is ordinarily given the task of furnishing the foundational tones of the harmony. Its range extends to about $b\flat$. Sustained tones are varied by occasional *pizzicato effects.* Beethoven introduced the fashion of giving to the bass rushing scale passages which stand out with great power. Modern composers have secured weird and characteristic effects by dividing the basses into separate groups.

Vibrating air-columns.

We must now treat of a numerous class of instruments in which the tones are produced by *vibrating columns of air.* There are two divisions of these, named respectively the "wood-wind" and the "brass," from the materials of which they are constructed.

The wood-wind.

Three groups of instruments make up the wood-wind, of which we shall first study the *flute family*, headed by the modern *concert flute*.

The flute.

The latter consists of a long narrow tube having the same diameter throughout (Fig. 96). One end is closed, while the other is left open; and near the closed end is a circular orifice across which the player blows, in order to set the interior air into vibration. By opening or closing six smaller holes, of which the player manipulates three with the fingers of each hand, the length of the air-column is changed and the tones of the diatonic scale are formed. Other holes, closed by valves, may be opened to obtain chromatic notes.

Fig. 96. Boehm Flute. Length, 26½ in.

Its registers and quality.

Starting at c' the range extends upward to about bb^{iv}. For the lowest octave the fundamental tones are used; but to sound tones in the second octave it is necessary to "overblow" the instrument, so that the first upper partials are heard instead of the fundamentals. Still higher partials are evoked through the rest of the compass. While the form of the flute would naturally give rise to the entire series of upper partials, the friction of the air along the sides of the narrow bore destroys most of them, so that in the lower octave or "register" the tone is sonorous but somewhat hollow, the middle register is sweet and melodious, and the highest register is more brilliant and bird-like.

Its possibilities.

Formerly made of wood, flutes are now constructed also of metal. Most agile of all wind instruments, they are at home in all kinds of running passages and in quickly repeated or "double-tongued" notes. While used in the orchestra to give brilliancy by reinforcing the tones of other instruments, the flute also renders solo melodies or runs with much charm.

A small flute called the *piccolo* (Fig. 97), having a compass

an octave higher than the instrument just described, is the only other member of this family which has orchestral significance. Its clear and sharp middle register is useful for special effects, such as the whistling of the wind or the rustling of leaves.

The piccolo.

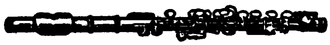


Fig. 97. Piccolo. Length. 12¾ in.

Next among the wood-wind comes the *oboe family*. This has four principal members, all conical in form, enlarging gradually from the mouth-piece to the other end, which is bell-shaped. Their most distinguishing characteristic, however, is the double reed which acts as the motor and which consists of two thin slips of cane placed nearly in contact and attached by silk to a small brass tube that is inserted in the end of the wooden part of the instrument. The player, holding this reed in his mouth, breathes gently into it, producing vibrations which cause the air in the main tube to sound. Regulated in length by holes and keys arranged on the same principle as those of the flute, the air-column gives out tones of different pitches, forcing the flexible reed to conform to its vibrations (page 78). A penetrating quality results from the emphasis of high upper partials in the full harmonic series that is present.

Characteristics of the oboe family.

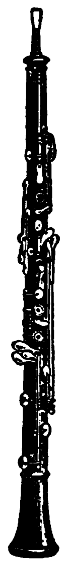


Fig. 98. Oboe. Length, 24¼ in.

The *oboe proper* (Fig. 98) is the treble member of this family, having a normal range from *bb* to *g'''*. When the finger holes are opened in the proper succession the scale of D major is sounded. Other tones are produced by using the keys. Three registers are formed as in the case of the flute and of these the middle is the most agreeable, since the lower is harsh and the upper piercing. Its dominant character makes the oboe largely a solo instrument, in which capacity it is especially identified with expressive melodies of a pastoral style. Moderately quick scale and

The oboe.

arpeggio passages are possible, although difficulties are experienced in connection with remote flat keys. Owing to the small amount of air necessary to excite vibrations, the player is obliged constantly to hold his breath in check, and must therefore frequently cease playing, to avoid undue strain.

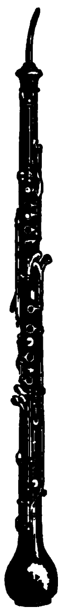


Fig. 99. English Horn (Cor Anglais). Length 35½ in.

The English horn.

Identical with the oboe in shape, except that it is somewhat larger and has a bent crook for a mouthpiece, is the *English horn* (Fig. 99). Its compass is a fifth lower than that of the oboe, to which it acts as alto, and extends from e to $b\flat''$. For convenience in changing from one to the other instrument its notes are written in the oboe compass, so that each actually sounds a fifth lower than it is notated. Its tones, less brilliant than those of the oboe, have a mystic, melancholy character. Quick passages are unsuitable for it.

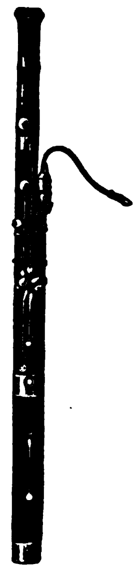


Fig. 100. Bassoon. Length, 4 ft. 4 in.

The bassoon.

An instrument of great range and agility is the *bassoon*, the bass of this family (Fig. 100). Its tube, nearly nine feet long, is given a more available shape by doubling it upon itself so that it resembles a bundle of fagots (whence its Italian name of *fagotto*). A brass crook connects the unusually large double reed with the wooden tube. The compass of three octaves, from $B\flat_1$ to $b\flat'$, has the usual three registers, of which the lowest is thick and unmanageable in the lower tones, the middle melodious, and the upper sweet, resembling in quality the tones of the violoncello. There is much variety in the orchestral use of the bassoon. It may

furnish the bass for harmonies or reinforce melodies, or it may play solo melodies or running passages which, especially when *staccato,* have a humorous effect that has earned for the bassoon the epithet of "clown of the orchestra."

Fig. 101. Contra-Bassoon. Length, 6 ft.

The contra-bassoon.

Only occasionally does the low-pitched *contra-bassoon* appear in the orchestra (Fig. 101). Proportionally an octave lower than the bassoon, its range is only from $C_{,}$ to *Eb*. Owing to the great length of its tube, which is about sixteen feet, rapid passages are not practicable.

Fig. 102. Clarinet. Length, 28 in.

Single-reed instruments.

There are two families of instruments which have as motor a single, rather than a double reed—the *clarinets* and the *saxophones*. Heading the first of these is the *clarinet proper,* like the oboe in that it consists of a wooden tube with a mouthpiece at the end (Fig. 102). In the mouthpiece, which is of wood or ebonite, is a broad strip of cane narrowed to a fine edge at the upper part. Pressed against the lower lip of the performer and excited by his breath, this sets into sympathetic vibration the air-column in the long tube, to which the mouthpiece is affixed. This tube, differing from that of the oboe, is in the form of a cylinder rather than a cone, having a small bell-shaped end. Its difference in shape causes it to stand to the oboe in the relation of a closed pipe to an open (page 64), with the result that its tone is an octave lower in pitch in proportion to its length, and that only the odd series of partials is produced.

The clarinet.

On account of the latter fact the key mechanism is unusually complicated: for since the third partials, at

distances of twelfths above the fundamentals, are the ones first produced by overblowing, the series of fundamental tones must be extended through a twelfth in order to meet these and complete the scale. For instance, the lowest note *e* overblown gives *b′*, a twelfth above. The result is the formation of a fourth register, as shown in Fig. 103.

Its key mechansim.

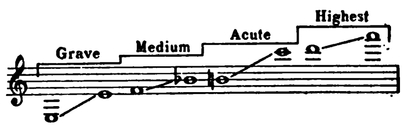


Fig. 103.

Of these registers the *grave* and the *acute* are the most important, since the dull character of the *medium* and the piercing quality of the *highest* impair them for musical purposes. Rich and mellow tones are found in the *grave* or *"chalumeau"* register, while those of the *acute* are clear and round.

Its registers and quality.

Owing to difficulties in fingering the performer can play in only a limited number of scale-keys on a single instrument: hence clarinets of different pitches are provided. These are *transposing* instruments: that is, their music is written as if for the clarinet built on the *C* scale. Indeed, on account of their better quality the clarinets in *B*♭ and *A* are used more often than the one in *C*, the first sounding *B*♭ and the second *A* when the written *C* is played, and the other tones maintaining the same relative distances.

Transposing clarinets.

Besides possessing exceptional beauty of tone-quality, the clarinet is able to graduate the intensity of its tone more than any other wind instrument. Because of its wide range and possibilities of passage work it is used in military bands in place of the violin. Again, its sustaining power is exhibited in rich and poetic melodic work.

Possibilities of the clarinet.

Passing over the *alto clarinet* or *basset horn,* not often now used in the orchestra, we come to the *bass clarinet,* shaped

The basset horn and bass clarinet.

like the ordinary clarinet but with a crook to the mouthpiece and the lower end bent so that the bell points upward (Fig. 104). Several of these instruments are in use, of pitches corresponding to those of the clarinets, but an octave below them. Their rich and telling tones sometimes assert the bass of the harmony and sometimes appear in singing melodies.

Fig. 104.
Bass clarinet. Length, 3 ft. 3 in.

Saxophones.

Saxophones are employed chiefly in military bands. While they have a single reed, they differ from clarinets in that their tubes are conical. On account of their shape they are generally classed among the wood-wind, although they are made of brass.

Characteristics of brass instruments.

Brass instruments differ from the wood-wind chiefly in the manner in which their vibrations are excited. Each consists of a conical tube ending in a bell and capped by a metal mouthpiece. Vibrations are excited in the latter by the lips of the player, and are thence transmitted to the air in the tubing. Acting as membranous reeds, the lips produce by their proper adjustment or *embrochure* the various tones of the harmonic series, generally obtaining the fundamental either not at all or with difficulty.

The natural horn.

When the mouthpiece is funnel-shaped and the tube very long in proportion to its diameter, the production of the higher partials is favored. Such conditions exist in the *"natural" horn,* of which the tubing, coiled

up for convenience, is from 9 to 12 feet in length. With the "natural" horn, employed by the classic masters, it is impossible without altering the length of the tube to play the harmonics in more than one key, although any tone may be dropped a half step in pitch by thrusting the hand into the bell and thus producing "stopped" tones, muffled in quality. Normally tuned in *C*, the natural horn is made to sound in other scales when its tube is lengthened by the insertion of metal "crooks." Like the clarinet it then becomes a transposing instrument, since its music is still written in *C*, although sounding in a different key. Each note of the horn in *F*, for instance, sounds a fifth lower than written. The horns in *F*, *E* and *E*♭ are the most common.

In the modern orchestra the *valve horn*, popularly known as the *French horn* (Fig. 105), is generally employed in place of the natural horn.

The valve horn.

It was first employed by Halévy in *La Juive*, 1835, and Schumann was the first German composer to use it. By the use of three pistons which, when pressed down singly or in combination, change the pitch anywhere from one to s' semitones the trouble of inserting different crooks is obviated. Thus the player is able to obtain the full chromatic scale without difficulty. On the valve horn in *F*, for instance, all the tones from $B_{,}$ to c'' derived from the fourth to the twelfth partials, can be played, while the second and third partials are also possible. Horns are used in pairs in the orchestra, half the players taking the higher notes and the others the lower; since on account of difficulties

Fig. 105. Valve-horn. Length, 22¾ in.

in adjusting the lips players prefer to specialize in certain parts of the scale. The mellow yet sonorous tones of the horn are sometimes used in lively passages, such as hunting fanfares, but are still more effective in solo melodies of a sustained character.

The trumpet.

A kindred brass instrument is the *trumpet,* which differs from the horn in that its tube is but half as long and is bent differently. The diameter of the tube is but 3/8 of an inch from the mouthpiece until it approaches the bell, when it widens out. The mouthpiece is shaped hemispherically, like a cup. By the trumpet in *C* the full series of upper partials as far as the twelfth is obtainable, while those in other keys are made possible by the addition of crooks, in which case the written music is transposed. Valve-trumpets (Fig. 106) are now generally used in place of the original "natural" instruments, with the preference given to those in *Bb* and *A.* The practical range is from *e* to about *bb″*.

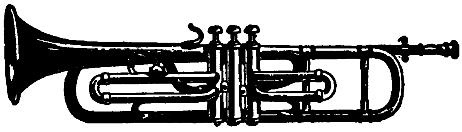


Fig. 106. Valve-trumpet. Length, 22½ in.

Its quality.

The louder tones of the trumpet have a ringing quality that easily dominates the full orchestra; while the clearness and purity of its soft tones are employed for distant or mystical effects.

Characteristics of the other brass instruments.

All the other brass instruments have cup-shaped mouthpieces, and tubes of which the bore is of greater diameter than that of the horn or the trumpet. The effect of this condition is to produce tones of a full and round quality but lacking the brilliancy given by the high upper partials.

The cornet.

As a substitute for the trumpet the *cornet* is frequently used on account of the facility with which it can be played, exceeding that of any other brass instrument. Of the *Bb* cornet the tube is but 4½ feet long, so that its

pitch is an octave higher than that of the corresponding trumpet. In most other respects the two instruments are similarly constructed; but as only the lower partials are obtainable on the cornet its tone is far less commanding and sensitive in quality.

The trombone.

In the *trombone* (Fig. 107) very perfect intonation is made possible by a long sliding section of tube which fits closely into the original tube of the instrument, and is perfectly under the control of the performer. When this slide is closed the instrument is said to be in the first position, in which case the fundamental and seven partials

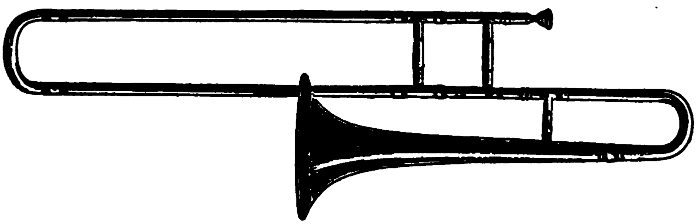


Fig. 107. Trombone.
Length, closed, 3 ft. 9 in.

can be obtained. By pulling out the slide, six other positions are produced, each sounding tones a half step lower than the previous one, although the fundamental is not obtainable in the lower positions. Evidently the same tone can frequently be produced in different registers. The notes are sounded as written.

Kinds in use.

Of several sizes in which trombones are made the *tenor trombone* in $B\flat$ is now most common, sometimes supplemented by the *bass trombone*. The normal compass of the former is from E to d'' and of the latter from $B_{,}$ to f'. The trombone tone is rich, even and sonorous.

The bass tuba and the ophicleide.

Three trombones frequently form a quartet with the *bass tuba* (Fig. 108), to produce a soul-stirring combination that resounds above the entire orchestra. The latter [redacted] mammoth instrument has four pistons, giving a chromatic range from $F_{,}$ to $b\flat'$. It has now sup- [redacted]

planted the savage *Ophicleide,* which was fingered by holes in the sides.

The harmonium, American organ and concertina.

We have now to speak of those wind instruments which are played by a key-board mechanism. Less important types are the ***harmonium, American reed organ*** and ***concertina.*** All of these have as vibrators free reeds (page 77), which are somewhat strident in tone, since this is not reinforced by pipes. In the harmonium the air is forced from the bellows through the reeds, and in the American organ it is sucked through the reeds into the bellows. Concertinas are furnished with fourteen notes to the octave, having separate reeds for *D♯* and *E♭*, and for *G♯* and *A♭*.

Fig. 108. Bass Tuba. Length, 3 ft. 3 in.

The pipe organ.

The most elaborate of all wind instruments, and one capable of producing an infinite variety of effects throughout its entire compass, is the *pipe organ.* Its tones are obtained from a multitude of both flue and reed pipes, the latter having either free or beating reeds (page 77), and all varied in quality by differences in shape and materials. A row of pipes of any given quality is made ready for action by drawing out the proper "stop"; and when a key is depressed a valve is opened in the corresponding pipe, thus allowing the wind to enter which causes the pipe to "speak." Stops are also of different pitches. Those called *eight-foot stops,* from the theoretical length of their lowest pipe, give the pianoforte pitch, while those of sixteen feet give an octave lower, those of four feet an octave higher, and so on. Thus the range extends to the limits of audibility in either direction,

although the keyboards or *manuals* each cover only five octaves. These manuals vary in number from one to four, and are supplemented by a row of *pedal* keys 2½ octaves in extent, played by the feet. Each manual is a complete organ in itself, although combinations of the manuals among themselves and with the pedals are made possible. Thus the organ is not properly one instrument but a group of instruments, placed within the power of a single performer by intricate mechanisms that govern wind supply, stop and key action and combinational devices. By the development of its limitless resources and the final application of electricity to secure its connections the organ has become a monument to the mechanical genius of man.

Percussion instruments: drums.

Finally in our catalogue come the *percussion instruments,* which, although generally productive of mere sound rather than tone, are yet often necessary for the emphasis of rhythm and for the capping of a climax. The most musical of these are the *kettle-drums* or *timpani,* of which at least two are found in the orchestra (Fig. 109). Each consists of a large and hollow brass hemisphere across which is stretched a membrane that can be tuned through the compass of a fifth by keys at the sides. Felt hammers impinging upon this membrane produce a well-defined tone, which can thus emphasize important points in the compositions. The *bass drum* and *snare drum* are only occasionally employed in the orchestra, and have no definite tone.

Fig. 109. Kettle-drum, Diameter of head, 24½ in. and 27½ ins.

Metallic instruments of percussion are represented in the orchestra by various kinds of *bells,* the *triangle, cymbals,* and

Metallic instruments.

gongs. Many sensational devices are employed by modern composers for special illustrative effects. These, however, can scarcely be classed among musical instruments.

The following table shows the compass of the principal instruments of the symphony orchestra of to-day. It gives the actual pitch of the instruments with the usual range for orchestral purposes. In solo work the range is more extended.

COMPASS OF THE INSTRUMENTS OF THE ORCHESTRA
(Showing the actual pitch and the range for orchestral purposes)

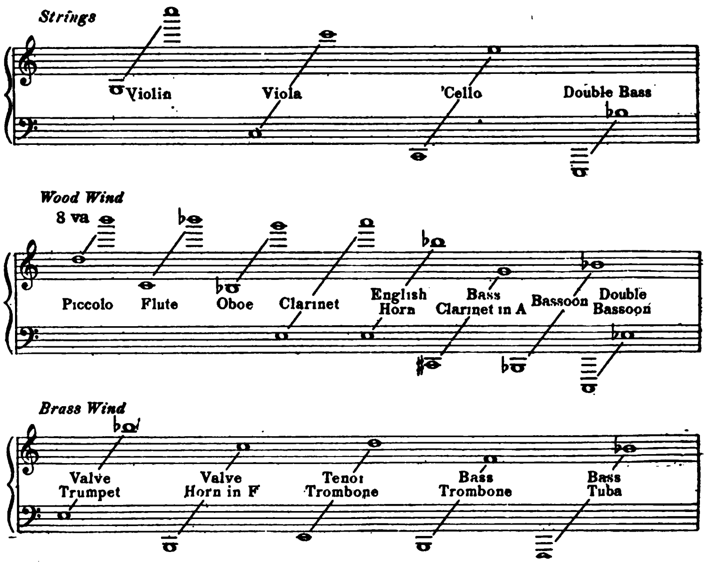


Fig. 110.

In the development of the modern orchestra there has been a constant advance in the knowledge of how to combine instruments most effectively, of the best proportions in which to employ them, and of the most effective means of utilizing their individual characteristics. Thus the orchestra has become a mammoth instrument which is capable of giving

expression to every shade of musical feeling, and which, moreover, when combined with voices by a genius like Wagner, apparently attains the acme of intensity in the utterance of emotion.

SUMMARY

LET us close with a restatement of the groups of instruments just studied. Those used infrequently or not at all in the orchestra are preceded by an asterisk (*). After each orchestral instrument is placed a number indicating how many of its kind are listed in the personnel of the Boston Symphony Orchestra (1911). With the conductor, the band of performers in this organization at present numbers exactly one hundred.

I. STRINGED INSTRUMENTS:

Plucked:

- *Guitar,
- *Mandolin,
- Harp (1).

Struck:

- *Pianoforte.

Bowed:

- Violin (16 first, 14 second),
- Viola (10),
- Violoncello (10),
- Double Bass (8).

II. WIND INSTRUMENTS:

Wood-wind:

- Flute (4),
- Piccolo,
- Oboe (3),
- English Horn (1),
- Bassoon (3),
- Contra-Bassoon (2),
- Clarinet (3),
- Bass-Clarinet (1),
- *Saxophone.

Brass:

- Horn (8),
- Trumpet (4),
- *Cornet,
- Trombone (3),
- Tuba (1),
- *Ophicleide.

Keyboard:

- *Harmonium,

*American Reed Organ,
*Concertina,
*Pipe Organ.

III. PERCUSSION INSTRUMENTS:
Kettle-drums (2),
*Bass Drum,
*Snare Drum (4),
Metallic Instruments.

REFERENCE LIST.

Barton, Chapter 8.
Lavignac, Chapter 2.
Pole, Chapter 4.
Stone, Chapter 1.
Zahm, scattered references.

For detailed accounts of instruments and their use, consult also the following:

Ch.-M. Widor, "The Technique of the Modern Orchestra." (Joseph Williams, London, 1906.)
E. Prout, "The Orchestra," 2 volumes. (Augener & Co., London, 1897.)
K. Schlesinger, "The Instruments of the Modern Orchestra," vol. 1. (William Reeves, London, 1910.)
D. G. Mason, "The Orchestral Instruments and What They Do." (The Baker and Taylor Co., New York, 1909.)
W. J. Henderson, "The Orchestra and Orchestral Music." (Charles Scribner's Sons, New York, 1902.)

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